Phosphate fixation and the response of maize to fertilizer phosphate in Kenyan soils

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Phosphate fixation and the response of maize to fertilizer phosphate in Kenyan soils

Dirk van der Eijk

Proefschrift

ter verkrijging van de graad van doctor
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Stellingen

1. In veel landbouwsystemen is de 'low-input strategy' een beter passende bemestingsstrategie dan de 'high-input strategy'.
   - *Dit proefschrift*

2. De beschikbaarheid van het meststoffosfaat voor planten wordt meer bepaald door de intrinsieke eigenschappen van de meststof en de dosis en wijze van toediening, dan door de eigenschappen van de bodem.
   - *Dit proefschrift*

3. Veeljarige veldproeven zijn onmisbaar om modelconcepten voor fosfaatfixatie te toetsen.
   - *Dit proefschrift*

4. De methodiek waarmee de fosfaatsorptie in het laboratorium wordt bepaald simuleert de veldsituatie onvoldoende. Het adviseren van de standaard P gift (SPR) op basis van een fosfaatsorptie-isotherm, zoals voorgesteld door onder andere Warren (1992), is derhalve onvoldoende gegrond en leidt in de praktijk tot een overmatig gebruik van meststoffosfaat.
   - *Dit proefschrift*

5. Het ontstaan van het Victoriameer ongeveer 12.000 jaar geleden heeft niet alleen geleid tot een evolutionair interessante ontwikkeling van haplochromine vissen behorend tot de familie van de cichliden, maar ook mede gezorgd voor een aangenaam klimaat in het Kisii gebied in Zuid-West Kenia.

6. Het voorstel om ook op fosfaatverzadigde gronden een fosfaatoverschot toe te staan van 20 tot 40 kg P_2O_5 per ha per jaar (Integrale Notitie "Mest- en ammoniakbeleid", 1995) is bemestingkundig fout, milieukundig onaanvaardbaar en, vanuit de optiek van de fosfaattekorten in veel tropische gronden, moreel te verfoeien.

7. Om de door het kabinet voorgestelde omslag van "multifunctioneel" naar "functioneel" saneren tot een succes te maken (Interdepartementaal rapport "Gerede grond voor groei", 1997), is dringend een brede discussie met de grondgebruikers noodzakelijk over de maatschappelijk gewenste bodemkwaliteit voor de verschillende bodemgebruiksfuncties. Deze discussie zou moeten uitmonden in wettelijk vastgelegde functionele bodemkwaliteitseisen.

8. Immobiele (historische) bodemverontreinigingen zouden voortaan beschouwd moeten worden als een deel van ons archeologisch bodemarchief en alleen dan verwijderd moeten worden als deze in de contactzone van de bodem voorkomen of bij ondergrondse bouw.

9. Het besluit van maart 1995 van het voormalige provinciale bestuur van Zuid-Holland om tot de aanleg van het Strategisch groenproject "Het Bentwoud" over te gaan is op oneigenlijke gronden en tegen de wil van de streek genomen. De sindsdien ontstane patstelling kan worden doorbroken door het toen onvoldoende gewogen streekalternatief "Het Bentveldplan" alsnog als basis voor de voorgenomen landinrichting van het gebied te nemen. Dit temeer omdat, sinds het Bentwoudconcept bedacht is, de inzichten over de ontwikkeling van natuur, recreatie en bos in het landelijke gebied veranderd zijn.

10. Natuurproductiebetaling bij agrarisch natuurbeheer vergroot niet alleen op een doelmatige wijze de natuurwaarden in het landelijk gebied maar draagt ook bij tot een betere verstandhouding tussen burgers en boeren.

11. In een waterrijke woonomgeving draagt het dragen van een zwemvest door spelende jonge kinderen bij tot een vermindering van het aantal verdrinkingsgevallen. Voor zowel ouders als kinderen is deze methode geruststellender dan het aloude dreigen met de "Bullebak" uit het volksgeloof.

12. Als de drie noordelijke provincies zich zouden afscheiden, zoals voorgesteld door de actiegroep "Nieuw Forum", vergroot dit de kansen op olympische medailles voor de Hollanders en Friezen bij de komende winterspelen in Nagano, hetgeen met name voor de 1500 meter rijders een aantrekkelijk vooruitzicht is.

Stellingen bij het proefschrift 'Phosphate fixation and the response of maize to fertilizer phosphate in Kenyan soils'.

Dirk van der Eijk, Wageningen, 22 oktober 1997

Voorwoord

Met het onderzoek in dit proefschrift heb ik me begeven op meerdere vakgebieden: bodemvruchtbaarheid, bemestingsleer, plantenvoeding, bodemchemie, mineralogie en tropische bodemkunde. Bovendien is het onderzoek uitgevoerd onder minder gebruikelijke omstandigheden. Zo zijn de veldproeven niet uitgevoerd in een vertrouwde omgeving van een proefstation, maar op akkers van boeren verspreid over een groot gebied en daarmee afhankelijk van de goodwill van de lokale bevolking en de toestand van de wegen. De breedte van het onderzoek en de omstandigheden in Kenia met het multidiciplinaire Training Project in Pedology als basis, heb ik als zeer inspirerend ervaren. Het risico dat een dergelijk onderzoek zou mislukken was groot. Dat dit niet is gebeurd is te danken aan de medewerking en inzet van velen zowel in Kenia als Nederland. Zij allen hebben direct of indirect bijgedragen aan de totstandkoming van dit proefschrift. Hiervoor wil ik hen van harte bedanken.

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ABSTRACT

Eijk, D. van der (1997). Phosphate fixation and the response of maize to fertilizer phosphate in Kenyan soils. Doctoral Thesis. Department of Soil Science and Plant Nutrition, Agricultural University Wageningen, The Netherlands, 200 pages, 44 figures, 3 photographs, 28 tables, 10 appendices, 270 references. English with Dutch summary.

In tropical soils, plant growth is often limited by a low P availability. In addition, these soils often have high P-fixation capacities due to high amounts of iron and aluminum oxyhydroxides. Furthermore, small-scale farming systems in which subsistence crops are produced for local markets are common in the tropics. Such conditions exit in South West Kenya, in the Kisii area, where this study was carried out.

The overall aim of the study was to improve our understanding of fertilizer P - soil - maize crop interactions and, thereby, to increase the yield response and improve the P recovery and utilization in plants. Initial and residual yield responses to fertilizer P applications; P uptake in plants, as well as P distribution and utilization within the plants; apparent fertilizer P recovery; and dissolution, transport and sorption of fertilizer P in the soils were studied under field conditions during three successive growing seasons. This was done within the concept of the low-input strategy, whereby the high-input strategy was used as a reference.

The soils were classified as Ultisols and Mollisols, or as Nitisols and Luvic Phaeozems. They were low in available native P (P-Olsen 1.6 to 3.2 mg/kg) and had medium to high P sorption capacities (445 to 870 mg/kg) measured under laboratory conditions. Total P ranged from 490 to 1,035 mg/kg. Triple superphosphate was used as P fertilizer and hybrid maize as test crop.

Good initial and residual yield responses were found in all soils even at low P application rates. The concept of P-fixation, as defined in this study, was not appropriate for the soils in the Kisii area. The second 'slow' phase of the fixation process was shown to proceed at a very slow rate under field conditions. Thus, P fixation is much less of a problem for farmers than expected. When P limited grain yield, the relationship between grain yield (z) and P in plant (y) could be described by the equation: $z=620(y-0.50)$. The efficiency of utilization increased with P application to about 550 kg/kg at P rates of 22 to 131 kg/ha and decreased at higher rates due to a luxurious P uptake. Granular fertilizer residues with P in the form of Fluorapatite, Brushite and an amorphous P compound could be recovered in the soil until the end of the trials, about 600 days after application. Fertilizer P was retained in the soil immediately surrounding the residual fertilizer granules to total P values up to > 8,000 mg/kg, which was much higher than predicted from the P-sorption studies in the laboratory. Available P levels (P-Olsen) in the P-enriched soil volume were high, up to > 800 mg/kg. The available fertilizer P fraction (ΔP-Olsen/ΔP total) remained fairly constant with time. It was suggested that the number of roots, i.e. root surface area, present in the small P-enriched volume was the limiting factor in fertilizer P uptake. As a result, the apparent P recoveries per crop were low. They were about 10 % each growing season at a P rate of 22 kg/ha.

Subseed placement at the start of each growing season is recommended, either placed alone or together with small amounts of cow dung. Then, plants benefit highly from both the starter-effect of freshly-applied fertilizer and the residual effect of previously-applied (residual) fertilizer. P application rates of 20 to 40 kg/ha (in P_2O_5: 45 to 90 kg/ha) are advised for maize. At these rates, slightly more P is applied than plants require for producing maximum grain yields and the P availability of the soils will gradually increase by enlarging the soil volume enriched with fertilizer P. This repeated subseed placement fits in well with the low-input strategy and is probably easily adaptable in tropical small-scale farming systems.

Key words: available P, cow dung, high-input strategy, Kenya, low-input strategy, P fixation, P sorption, P retention, P utilization, P recovery, P residual effectness, small-scale farming system, triple superphosphate, volcanic ash, Zea maize.

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1 INTRODUCTION

1.1 PROBLEM IDENTIFICATION

In many areas of the tropics, population growth is rapid and there is a rapidly growing demand for food. Therefore, cultivation of subsistence crops must be stimulated and production augmented. Unfortunately, most tropical soils, especially those which are used or will be used in the future for the production of subsistence crops, have low levels of chemical soil fertility, often caused by low levels of available phosphate. Consequently, yields are low or yields are initially high and decrease rapidly with prolonged cultivation. Furthermore, many tropical soils are able to fix large quantities of fertilizer phosphate, a main factor lowering the recovery of fertilizer phosphate by plants.

In many farming systems in the tropics, input of manures and fertilizers is still low and not sufficient to sustain the productivity of the soils. Bringing more land into cultivation causes many complications and is often not possible in the densely populated areas. Preference should therefore be given to raising the production of subsistence crops by increasing the fertility of the soils on which these crops are grown. Manures and fertilizers should then be applied to restore and improve the soil fertility and to compensate for the withdrawal and losses of nutrients during cultivation.

Ever since industrial production of phosphate fertilizers started in the second half of the nineteenth century, phosphate rock has been mined intensively and although world phosphate resources are large, the reserves of premium grade phosphate rock are small and running low. In order to continue production of the various phosphate fertilizers at present-day quality, more advanced technologies will be needed for mining less accessible resources and for upgrading low-grade phosphate rock. The expected increase in demand for phosphate fertilizers will probably accelerate the introduction of these technologies. More energy will be needed in the production process. Evidently, future production will only be possible at higher costs.

It is necessary to economize on the use of phosphate rock. Therefore, research should be aimed at increasing the crop's recovery of fertilizer phosphate. Such an increase in recovery can be attained by producing better fertilizers, by improving methods of fertilizer application, by creating more favourable conditions for uptake of fertilizer phosphate by plants, and by using crops and varieties that can efficiently take up and utilize fertilizer phosphate from the soil. Moreover, the phosphate in crop residues and waste products should be effectively and efficiently re-utilized, so that farmers become less dependent on the gradually decreasing amounts of phosphate rock-derived fertilizers.

Numerous studies addressing the recovery of fertilizer phosphate have been carried out. These studies have greatly increased our understanding of the behaviour of fertilizer phosphate in soil. Since the sixties and seventies, it has been suggested by prominent soil scientists (e.g. Young, Plucknett and Fox), that a single large amount of phosphate fertilizer should be applied to quench the phosphate-fixation capacity in the entire tilth layer of phosphate fixing tropical soils in order to increase the amount of plant available phosphate to a sufficiently high level. This high-input strategy requires, however, large investments and, therefore, has been controversial ever since. The alternative, the low-input strategy in which only a small volume of the soil is fertilized for each crop, has traditionally been favoured. However, its success depends on the assumption that all small farmers have the means and knowledge to effectively utilize small amounts of phosphate fertilizer each growing season. The discussion about the most valuable approach for remediating low-phosphate soils in the tropics, a high-input strategy or a low-input strategy, is still very relevant and up to date. For example, at the November 1996 meeting of the American Society of Agronomy and the Soil Science Society of America in Indianapolis, a plea for a diversification of strategies was made at a special symposium entitled 'Replenishing Soil Fertility in Africa' (Special publication ASA and SSSA in preparation). The question still remains where to apply which strategy and how.

1.2 AIMS OF THE STUDY

The research described in this thesis focuses on the recovery in maize of phosphate fertilizer applied to soils with very low amounts of available phosphate and medium to high P-fixation capacity. More particularly, it focuses on the improvement of methods of phosphate fertilizer application. It addresses the technical and agronomic aspects of the low-input strategy, using the high-input strategy as reference.

The study was carried out in South West Kenya in the Kisii area, as part of a multi-disciplinary project of the Agricultural University of Wageningen. The area is densely populated, with a fast growing population, that mainly subsists on agriculture. Zea maize is the staple food of the population. If phosphate fertilizers are applied, triple superphosphate is commonly used. Since many areas in the tropics are similar to the Kisii area, with respect to soils, climate, farming systems and stage of agricultural development, the area is representative for large areas in the tropics.

The overall aim of the study was to improve our understanding of the fertilizer phosphate - soil - maize crop interactions, and thereby to increase the maize yield response to phosphate fertilizer and to increase the recovery and utilization of fertilizer P in tropical soils with low levels of available phosphate. More specifically, the objectives were as follows:
1. to analyze and describe the phosphate status in dominant soil types of the Kisii area and to relate this status to parent material and soil type;
2. to study the compositional changes of triple superphosphate fertilizer and fertilizer P transport and sorption in various soils under field conditions;
3. to test the efficacy of various methods of fertilizer phosphate application with respect to initial and residual plant responses;
4. to assess the short-term (one growing season) and mid-term (three growing seasons) plant recovery of fertilizer P for various soils; and
5. to establish a basis for improved recommendations of phosphate fertilizer application with emphasis on the low-input strategy and using the high-input strategy as a reference.

Central to the study were the fertilizer - soil - maize plant interactions as encountered in the field. An integrated study involving laboratory and greenhouse experiments and extensive field trials was judged most appropriate for satisfying the objectives mentioned above. Experimental designs of the laboratory and field experiments were based on a literature review and a conceptual model of the behaviour of fertilizer phosphate in soil. No mathematical modelling was envisaged, simply because of the limited amount of knowledge of the fertilizer phosphate behaviour in Kenyan soils at the start of the study, and because of time constraints. However, the results may be useful as input for modelling the complex interactions between fertilizer P, soil and plant under tropical field conditions.

The experimental work of this study was carried out between 1976 and 1980. For various reasons, beyond the scope of the project, the study was interrupted for many years. Yet, the results can be judged still highly relevant and, therefore, worth publishing.

1.3 CONTENTS OF THE THESIS

Chapter 2 provides a general description of the area. The information gathered by the various partners in the multi-disciplinary project about the geology, geomorphology, soil types and land use in the area is summarised. This information was very helpful in the selection of the trial fields and facilitated the interpretation of the results.

Chapter 3 gives a brief overview of the literature on P in soil-plant systems. Subjects such as: the P cycle in nature; the production and agricultural use of P fertilizer; the P sorption and desorption mechanism; the P uptake and utilization in plants and the P fixation in tropical soils are reviewed.

Chapter 4 describes the concept of P fixation and definitions as used in this study. P fixation was found to be an ambiguous term in literature and, therefore, special attention is given to the definition of P fixation and how it is used in this study.

Chapter 5 presents a design for the field trials. The design is based on the physical conditions and farm management practice in the survey area (Chapter 2), the literature review (Chapter 3), the conceptual model of P fixation, as presented in Chapter 4, and the results of preliminary field trials in the Kisii area, pot trials in the greenhouse at Wageningen and laboratory experiments. Emphasis is laid on the investigation of methods that fit in with the low-input strategy.

The basic field trials were designed for three growing seasons. The results of the first season led to an accentuation of the hypotheses and to the design of additional field trials to be carried out for the next two growing seasons. In the last season, additional trials were started especially with a view to obtain a better understanding of the factors involved in the P-fixation mechanism, such as the behaviour of fertilizer P in the soil and plant root development.

Chapter 6 describes in detail the execution and management of the trials. Trial fields were selected on farmers' land. A form of trial management was chosen that was comparable with local farm management. Application of fertilizers, planting, weeding and harvesting were done manually.

Chapter 7 presents the results of the study. First, the crop yield responses are given. Then, P uptake and P utilization in plants and fertilizer P recovery are presented. Finally the results on the study of the behaviour of fertilizer P in soils are described.

In Chapter 8 the results are discussed. The discussion is conducted on the basis of the interactions between fertilizer, soil and plant.

2 DESCRIPTION OF THE AREA

2.1 GEOGRAPHY

The study was carried out in the Kisii area in South West Kenya in an area situated approximately between latitudes 0.3 ° and 1.0 ° S. and longitudes 34.3 ° and 35.0 ° E., which corresponds with the area covered by the quarter degree map sheet no. 130 of the 'Survey of Kenya' (Figure 1). A simplified cross-section through the area of South West Kenya is shown in Figure 2. Along this section, the sites selected for trials (see Chapter 5.4) are arranged according to their altitude and surface morphology of the area they represent.

2.2 GEOMORPHOLOGY

Wielemaker & Van Dijk (1981) distinguished two physiographic units in the survey area: 1) the 'Kisii Highlands', a hilly and rolling area in the centre, and 2) an area surrounding the Highlands at a lower altitude with a rolling and gently undulating topography.
The area is composed of a series of erosion surfaces, which have been lifted up and tilted westwards as a result of tectonic activity occurring since tertiary times. Wielemaker & Van Dijk (1981) distinguished five erosion surfaces. These are, from old to young: 'Kisii' (7, 10, 16), 'Magombo' (1, 2), 'Chepalungu' (6, 14, 15), 'Rongo' (4) and 'Magena' (9). The numbers between parentheses refer to numbers of experimental or sampling sites located on remnants of the corresponding surfaces. The Kisii and Magombo surfaces occur in the Kisii Highlands. The Chepalungu surface surrounds the Highlands, while the Rongo and Magena surfaces occur west of the Highlands. The other sites (3, 5, 8, 9, 11, 12, 13, 17) were located on flat or gently undulating areas which were too small to identify the erosion surfaces.

2.3 GEOLOGY

The majority of the rocks date from the Precambrian period (Huddleston; 1951). Tertiary deposits of lavas and ash originating from volcanoes in the Kavirondian Rift Valley are restricted to the area near Lake Victoria. These volcanoes were active from the Miocene till the early Pleistocene (King et al.; 1972). Quaternary ashes originating from Eastern Rift Valley volcanoes were apparently deposited throughout the area (Wielemaker and Wakatsuki; 1984). Their relative importance in the area decreases considerably in a westerly direction. At the eastern border of the 'Kisii Highlands', on hill crests of over 2,000 m above sea level and in flat-bottomed valleys throughout the area, the ash stratification has been fairly well preserved.
The early Precambrian rocks occurring west of the 'Kisii Highlands' consist mainly of rhyolites and to a lesser extent of andesites and basalts. Intrusive rocks and conglomerates occur locally and contribute to the geologic variation in this part of the area. The two most extensive intrusions are the 'Kitere' and Wanjare' granites.
The late Precambrian rocks in the Kisii Highlands consist of basalts and associations of felsites and andesites, and of rhyolites and tuffs. Quartsites interspersed between basalts and felsites cover minor areas but, due to their resistance to weathering and erosion, they presently stand out as high ridges running in a N-S direction through the area. These ridges have made a

considerable contribution to the topography of the area. Figure 3 shows the geologic pattern of the area.

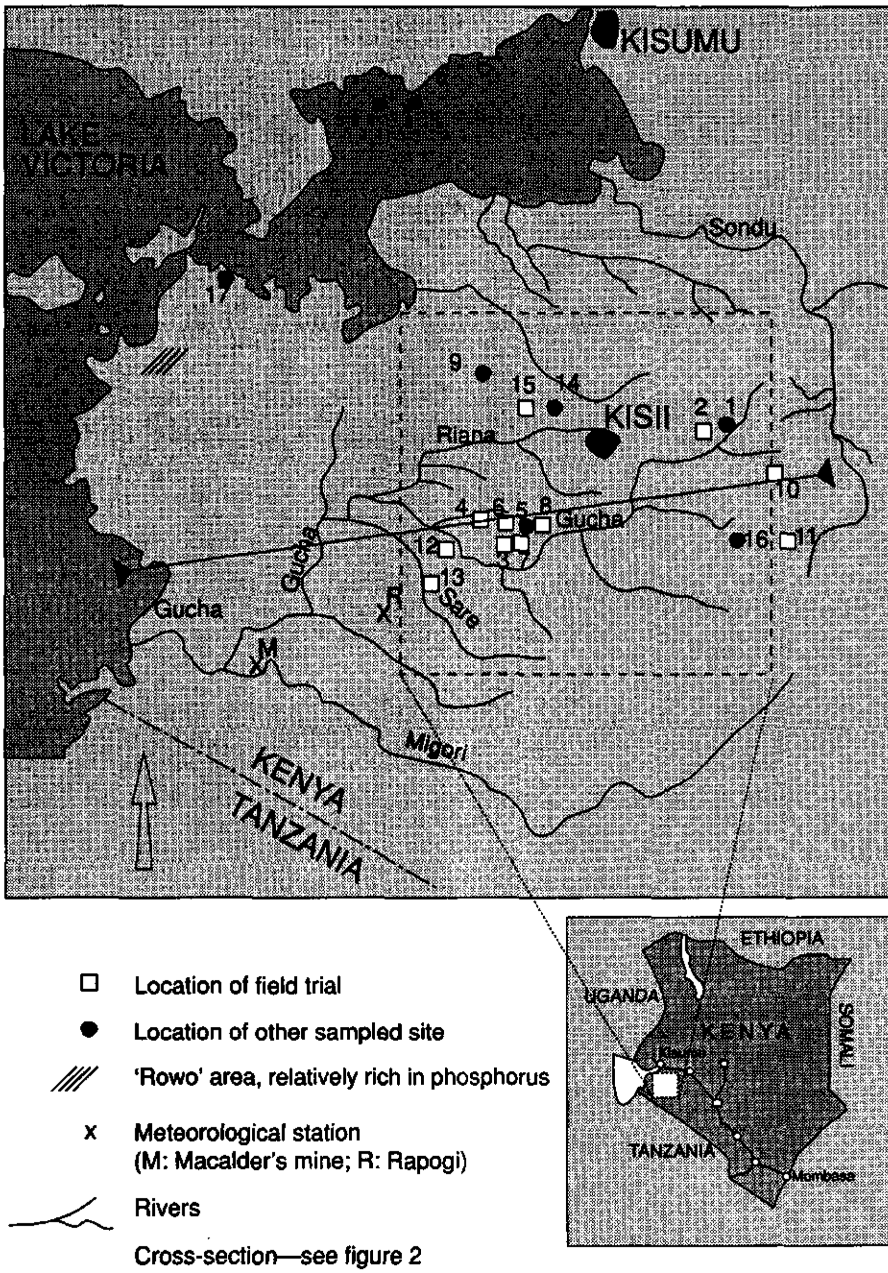


Figure 1. Situation of the study area in Kenya

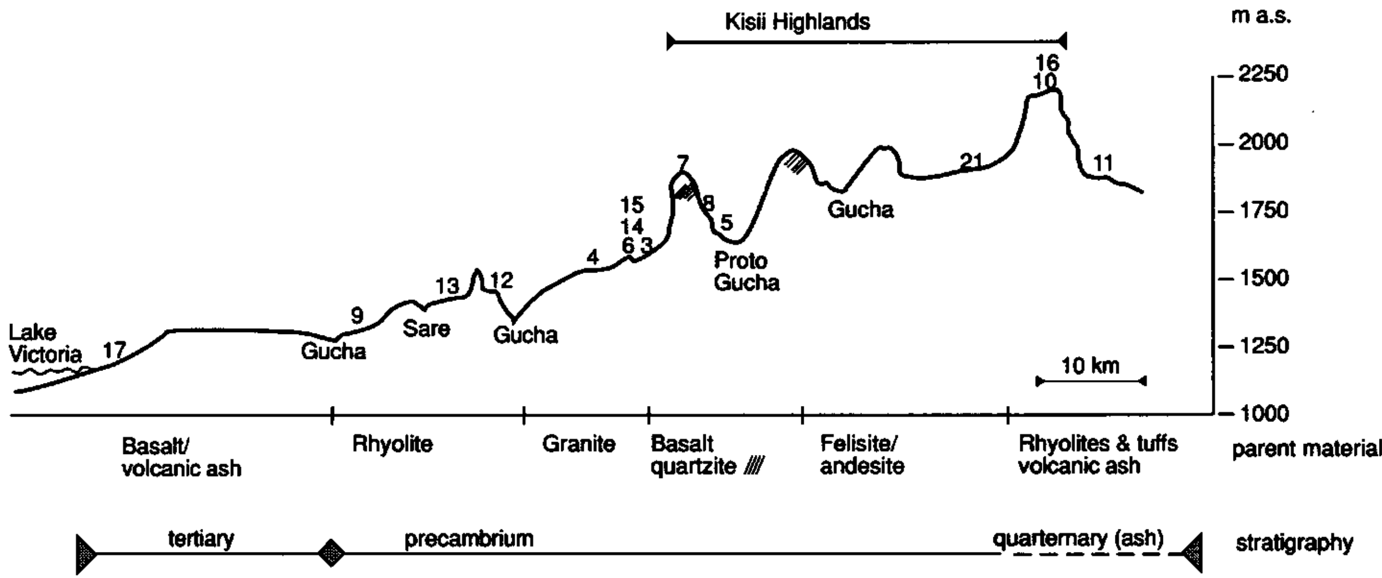
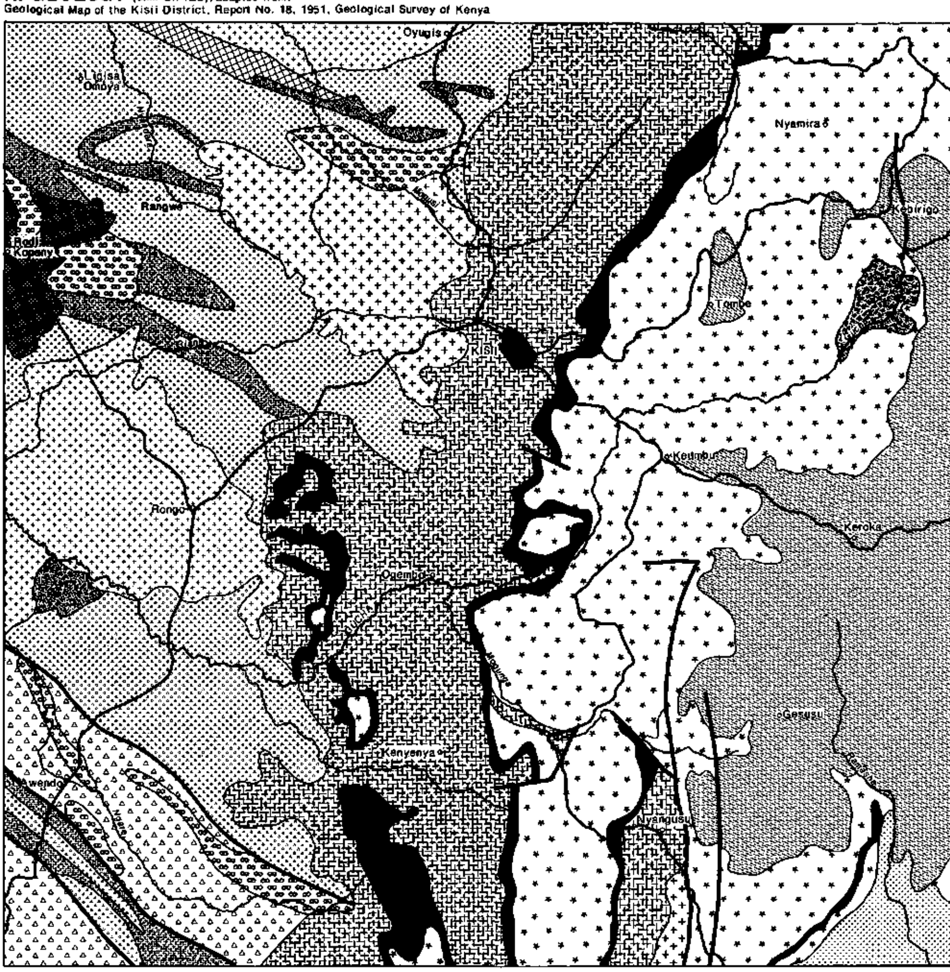


Figure 2. A simplified cross section (east-west) of South West Kenya and projected positions of trial fields and sampling sites.

MAP SHEET 130

Appendix 4 to Report No. 4 "Soils of the Kisii area"

A. GEOLOGY (SIMPLIFIED); adapted from:
Geological Map of the Kisii District, Report No. 18, 1951, Geological Survey of Kenya



STRATIGRAPHY	ROCK TYPE
Quaternary	volcanic ash deposits
Tertiary	nephelinites, nepheline basalts
Precambrium	
Bukoban	rhyolites and tuffs
Bukoban	felsites and andesites
Bukoban	quartzites and cherts
Bukoban	basalts
Kavirondian	conglomerates

STRATIGRAPHY	ROCK TYPE
Nyanzian	upper andesites
Nyanzian	rhyolites
Nyanzian	andesites and dacites
Nyanzian	basalts
Intrusives	
Post-Kavirondian	dolerites and lamprophyres
Post-Kavirondian	Wanjare granites and quartzdiorites
Post-Nyanzian	Kitere and Oyugis granites
	faults

Figure 3. Geological map of the study area

2.4 SOILS

Since the influences of factors affecting soil formation, such as tectonic and volcanic activity and drainage pattern, has varied considerably with time, the genesis of the soils in the area is rather complicated. Wielemaker & Van Dijk (1981) related soil formation partly to the development and ages of the erosion surfaces and partly to deposition of ash on these surfaces. For the younger Magena and Rongo surfaces and the part of the Chepalungu surface occurring west of the Highlands, they found a definite relation between the stage of soil development and the age of these surfaces, whereas for the older Kisii and Magombo surfaces, which had already been formed before the ash depositions started and which occur within a closer range of the source volcanoes in the Eastern Rift Valley, they assumed that soil formation was more related to the quantities and ages of these ashes. Since ashes were frequently ejected from Eastern Rift Valley volcanoes, it can be assumed that the ash, which reaches a thickness of over five metres at some sites in the survey area, is composed of several individual deposits. Consequently, soil formation has been frequently interrupted and soils have been regularly rejuvenated by these ash falls.

Due to variations in altitude and degree of dissection of the erosion surfaces, climate and drainage differ considerably from one area to another. In addition, in the geologic past climate changed considerably (Kendall; 1969) and drainage was affected by tectonic uplifts (Wielemaker & Van Dijk, 1981). Since both factors control the rate of weathering of rock and volcanic ash and also affect soil formation, they determine the type of soil that develops.

On hill crests covered with thick layers of volcanic ash, occurring in the eastern part of the Highlands at altitudes of about 2,150 m and on some crests east of the Highlands, the soils developed entirely in ash and still bear ash characteristics. Two of such characteristics can be observed in the topsoils. These have dark colours and low bulk densities. When wet, they are black (l0YR 1/1-2/2) and when dry, they are greyish (7.5YR 2/2-4/3). In dry conditions, their low bulk densities (0.85-0.90 g/cm^3) are obvious. The soils were classified according to the rules laid down in the Soil Taxonomy (Soil Survey Staff; 1975). The surface horizon, often extending to a depth of more than 50 cm, was thus classified as a pachic mollic epipedon, and the complete solum as a pachic andeptic Hapludoll.

On well-drained hill crests and slopes occurring at lower altitudes in the centre and west of the Highlands, the ash, becoming more intensively weathered, was transformed into reddish-brown soil material, thereby almost concealing its origin. In addition, soil animals (particularly termites) which occur in high numbers thoroughly mixed soil materials derived from ash and from underlying rock, so that the original ash stratification was disturbed (Wielemaker; 1984). Due to this weathering and disturbance, it has not yet been possible to determine to what extent the well-drained soils have developed in ash deposits or in underlying rock.
In poorly-drained water-logged soils occurring in some valley bottoms in the centre of the Highlands, the original ash stratification has been better preserved during weathering because of a low degree of animal activity.

Volcanic ash has probably contributed on well-drained soils to the formation of topsoils with a base saturation of 50 to 100 percent, with a relatively high content of organic matter and dusky colours. As a result of the substantial supply of the major nutrients P, K, Ca and Mg derived from ash constituents, and due to favourable climatic and soil physical properties, the soils of the Kisii Highlands can bear luxurious vegetation. According to Wielemaker (personal communication; 1986) the efficient recycling of nutrients by the soil fauna greatly contributed to the maintenance of the high nutrient levels of the topsoils. Above an altitude of about 1,700 m, organic matter has accumulated in the topsoil to organic C levels usually exceeding 40 g/kg. The dusky colours result from the accumulation of organic matter in the form of dark compounds in which organic matter is probably associated with ash-derived clay minerals. On the basis of these topsoil characteristics and of a colour contrast between topsoil and subsoil, the surface horizons of many well-drained soils were classified as mollic epipedons.

Due to the presence of a mollic epipedon and an argillic subhorizon that gradually develops and extends to depths of over 1.5 m below the soil surface, many well-drained soils were classified as typic Paleudolls. Locally, the sola of these typic Paleudolls developed to depths of more than 10 m. Where the argillic horizon was shallower than 1.5 m below the soil surface, soils were classified as typic Arguidolls, and where in addition the cation-exchange capacity of the soil in the argillic horizon was below 240 mmol per kg clay, oxic Arguidolls were distinguished. If, however, the base saturation of the soil in the argillic horizon decreases with depth or is below certain boundary values, the argillic horizon becomes the main diagnostic criterion for classification. For this reason, some soils of the Kisii Highlands having a mollic epipedon were, nevertheless, classified as Ultisols.

In general, within the survey area from east to west, from older to younger erosion surfaces, from hill crests to slopes with increasing gradients, the epipedon loses its mollic properties and becomes less diagnostic, while the argillic sub-surface horizon remains (Figure 4).

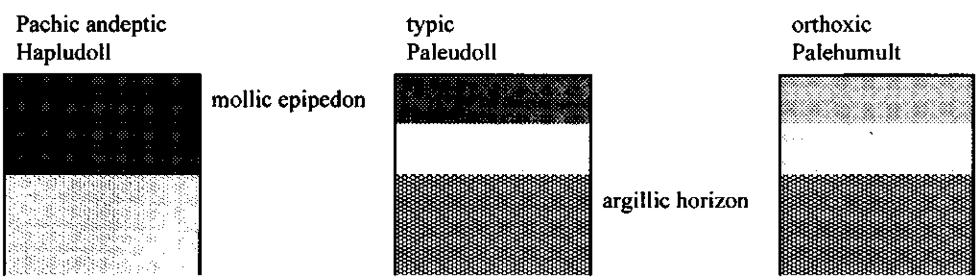


Figure 4. Soils of the study area.

For many soils west of the Kisii Highlands, the topsoils did not meet all requirements for a mollic epipedon, so that the argillic subhorizon was considered the main diagnostic criterion for classification. Deep soils were thus classified as Palehumult or as Paleudults, depending on whether their organic carbon contents in the upper part of the argillic horizon or in the first metre of the solum were above or below certain boundary values. Depending on whether the level of the cation-exchange capacity of the clay of the soil in the argillic horizon was above or below 240 mmol per kg clay, they received the adjectives typic or orthoxic. The less deeply developed members were classified as Tropudults. According to the classification system of the FAO/UNESCO, the soils were classified as Nitisols and luvic Phaeozems.

At soil family level, two families can be distinguished, being different in texture and belonging to different soil-temperature regimes. Most soils of the Kisii Highlands, underlain by either basalt or an association of felsite and andesite, belong to the very fine clayey kaolinitic isothermic family. Alternatively, most soils west of the Highlands, underlain by granite or rhyolite, belong to the fine clayey kaolinitic isohyperthermic family.

2.5 CLIMATE

The survey area has a climate typical of humid tropical regions of high altitude. The average air temperature varies with altitude from about 20 °C to 25° C and within a year shows fluctuations of less than 5 °C. The average annual rainfall ranges from about 1,400 mm at the lower altitudes west of the Kisii Highlands to about 2,000 mm in the centre of the Highlands. Rainfall is concentrated in two periods (Figure 5). These coincide with the biannual passage of the intertropical convergence zone. More rain falls from March till June (the long rainy season) than from August till November (the short rainy season). Periods of drought, caused by easterly trade winds, occur frequently during December, January and February and in July, thus separating the rainy seasons. At the peak of these dry periods sunshine lasts throughout the day, whereas during the rainy seasons clouds intercept a part of the solar radiation. Clouds usually form in the afternoon but, as the peaks of the rainy seasons approach, cloud formation starts earlier in the day, sometimes culminating in overcast skies all day.

The average daily global radiation varies with the seasons from about 1,600 J/cm^2 day during the rainy seasons to about 2,000 J/cm^2 day during the dry seasons. When the sky is completely overcast, it can be as low as about 800 J/cm^2 day, while on continuously sunny days, during periods of high inclination of the sun, it can be as high as about 2,500 J/cm^2 day.
Evaporation is inversely related to altitude. At Kisii town, the average annual evaporation from a free water surface recorded in a pan amounts to 1,890 mm. The daily evaporation varies with the seasons. In a dry season just before a rainy season starts, with low relative humidity of the air, high wind velocities, high global radiation and high temperature, it reaches a maximum, whereas from the peak until the end of the rainy season, with increased relative humidity of the air, reduced wind velocities, reduced global radiation and lower temperature, it reaches a minimum.

The presence of a vast expanse of water in the form of Lake Victoria plays an important role in the development of frequently occurring, daily, local, lake-land breezes which considerably affect climatic conditions, especially rainfall, in the survey area. During the day, because of differences in heat capacity and thermal conductivity between soil and water, the air above land is warmed up faster than above the lake. As a result, the relatively warm air above the land ascends and the relatively cold air above the lake is driven inland by winds in the lower atmosphere. These air masses, having been moistened by evapotranspiration above land and by evaporation above the lake, are driven by such winds towards the centre of the Highlands and, while they ascend there in thermal bells, the moisture in them condenses to form cumulonimbi. This process leads to heavy late-afternoon rains often occurring as thunderstorms and sometimes accompanied by hail. While depleting, the cumulonimbi are driven towards the lake by reverse winds in higher regions of the atmosphere so that the rain, which usually starts in the centre of the Kisii Highlands, spreads over the area. During the night, the lake-land circulation is reversed, leading to offshore winds in the lower atmosphere.

These local lake-land circulations give rise to the following climatic gradients from the lake shore to the centre of the Kisii Highlands. 1 Global radiation in the afternoon decreases as a result of cloud formation. 2 Rainfall increases (Figure 5). 3 The frequency of showers increases and rainfall distribution during the seasons becomes more uniform. 4 The length of drought periods shortens (Figure 5). The lake-land circulations also cause temporary differences in rainfall distribution over short distances, for instance from one valley to another, since rain falls in various local thunderstorms and showers. At the peaks of the seasons, however, the macro-climatic phenomena, such as the passage of the intertropical convergence zone and the occurrence of easterly trade winds, suppress these local lake-land circulations, so that they do not develop or are too weak to be of importance.

Since both dry and rainy seasons differ in duration and intensity from one year to another, weather conditions may vary considerably. Climatic factors such as the amount of rainfall to be expected in a growing season and the starting date of a rainy season, important for growing seasonal crops and for planning agricultural activities, may vary widely from year to year. The long rainy season usually starts in March and usually brings sufficient rain for satisfactory crop production. The short rainy season may start either in August, September, October or November, and rainfall may not be sufficient for proper crop production. Dry spells are also common during the short rainy season.

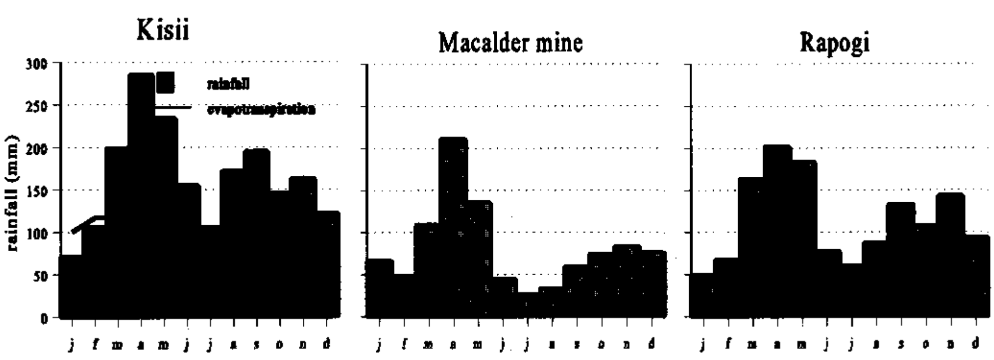


Figure 5. Monthly rainfall and evapotranspiration in South West Kenya (locations meteorological stations, see Figure 1).

2.6 LAND USE

All land is in agricultural use and is farmed in a traditional way in small family holdings. Cow dung is widely used as a manure but, unfortunately, supplies are short. Fertilizers are available, but they are little known and costly and, therefore, are hardly used. Bush-fallow is still a common practice in less densely-populated areas whereas, in more densely-populated areas, the 'bush-fallow' intervals have been shortened, or the practice has been stopped altogether.

The large areas of well-drained soils are in cultivation for producing subsistence crops, particularly maize, sorghum, millet, beans, cabbage and bananas, and for producing cash crops. At the time of the trials the major cash crops were: coffee, tea, pyrethrum, bananas and sugar cane. Most farmers grow several subsistence crops and often one or two cash crops. The crops are usually grown on very small plots either in monoculture or in various forms of mixed cropping. During bush-fallow intervals, the arable land is used for grazing. The small areas in valley bottoms with poorly-drained soils are exclusively used for grazing, while the few areas with very steep slopes are kept under wood used for timber or charcoal.

Maize is the most important food crop and, next to native varieties, hybrid maize varieties are used throughout the area. The long rainy season is the main growing season for maize. In the eastern part of the Kisii Highlands, maize is grown only during these long rainy seasons, while in the western part and west of the Highlands it is also grown during the short rainy seasons. Above an altitude of about 1,600 to 1,700 m, the growing season is longer than six months. This can be ascribed to the relatively low air and soil temperature and to the frequent occurrence of showers which retard the development and maturation of the maize crop. For growing maize in the rainy seasons above these altitudes, fields are planted once a year and, after the maize harvest, they either remain in fallow or are planted with other subsistence crops that mature within six months. Alternatively, fields below these altitudes may produce two maize crops per year. Such an intensive cropping system is practised only on relatively good soils.

3 LITERATURE REVIEW

3.1 P FERTILIZER RESEARCH IN RETROSPECT

Although P remained an unknown element until Brandt isolated it from urine in 1669, materials containing P such as manures, bones, guano and fish have been used as fertilizer in many farming systems since antiquity. Later P was identified in various materials, in plant tissue by Albinus in 1688, in bones by Gahn in 1769 and after 1779 also in inorganic materials, for instance in apatite (Mellor, 1947; Toy, 1973). The origin of P in plant tissue was discovered in 1804 by De Saussure. He stated that the soil supplies the ash constituents of the plants. This concept was further worked out by Von Liebig and became widely known and generally accepted after 1840 by the publicity given to Von Liebig's writings. The knowledge that P was an essential nutrient for plants, and that it was taken up from the soil, supported the idea that P fertilizers should be applied for improving and maintaining the productivity of soils. As a result, the use of P fertilizers had become common practice in agriculture by the end of the 19 th century (Hopkins, 1910).

Since circa 1850 research has been concentrated mainly on providing answers to the following questions:
- which type of P fertilizer should be applied to soils in order to obtain the highest yield responses or the highest profits?
- which methods are available for manufacturing more effective P fertilizers?
- which methods of application should be used in order to obtain the most favourable yield responses, the highest P recoveries in plants and the most efficient utilization of P in plants?
- which suitable methods are available for determining the P status of soils and plants?
- which methods should be used to predict the amount of P fertilizer needed to obtain optimal yields?
- which factors control the fixation of fertilizer P in soils.

In most field experiments on P-deficient soils, crops respond markedly to P application. Often, however, the fraction of fertilizer P recovered by the plants is low. According to Russell (1973), crops usually recover less than 10 percent of the applied amount in the first season, even if they respond well to the P fertilizer. In the succeeding growing seasons, the crop response to the remaining fertilizer P decreases rapidly and is usually too small to be determined in field experiments after three or four years. Russell mentioned that the total recovery after four years was often only 20-30 percent. Warren (1992) reviewed the literature on this subject for tropical African soils. Long-term P recovery studies are still scarce on tropical soils. Often the results show a wide variability from almost no response and recovery (Van der Zaag & Kagenzi, 1986), to residual responses lasting for at least about ten years and rather good recoveries (Child et al., 1955; Fox et al., 1968; Lathwell, 1979; Holford & Crocker, 1991). Sometimes poor recoveries were found, for instance Van der Zaag & Kagenzi (1986) found a recovery of only 1.2 % at a P application rate of 84 kg/ha with potatoes on a Rwandan highly P sorbing andosol. Sometimes rather good residual responses and recoveries were found. Child et al. (1955) mentioned a recovery of 21.8 % at a rate of 14.7 kg/ha within six months and 67.2 % within four years with Napier grass on an acid laterized red earth soil at Kericho, Kenya. Residual effects of at least nine years were recorded at high application rates on dark red latosols in Brazil and on highly P sorbing soils in Hawaii (Lathwell 1979,; Fox et al., 1978; Warren, 1992). Often the results are difficult to comprehend as part of the variability is caused by seasonal variation and differences in farm management during the trials. Through modelling, the interpretation of the results can be improved (Wolf et al.,1987; Janssen et al.,1987; Warren, 1992).

Knowledge developed in scientific disciplines such as chemistry, physics and plant physiology has been successfully applied in soil fertility and has contributed much to our understanding of the reactions in which fertilizer P is involved after having been applied to a soil. Furthermore, it has contributed to the production of more effective P fertilizers and to the development of more efficient application methods.

Although the grinding of bones and phosphate rock was first practised to enable a uniform distribution of the fertilizer through the soil, it was later encouraged to improve the availability of the fertilizer P to plants. Grinding enlarges the specific surface of the phosphate minerals and so increases their dissolution rate. In practice, grinding often proved to be profitable.

Acidulation of phosphate rock and bones was found to make P more available to plants, as during acidulation sparsely soluble apatite, which is the main P mineral in phosphate rock and bones, is converted into highly-soluble monocalcium phosphate monohydrate. If measured in terms of yield responses, acidulated P fertilizers have often proved to be better than non-acidulated fertilizers. If measured in terms of profit, however, the advantage is reduced by the higher costs of production. Whether acidulated or non-acidulated P fertilizers should be recommended to farmers has been a difficult and controversial matter ever since 1847, when acidulation of phosphate rock started on a commercial scale (Hopkins, 1910; Sanchez & Uehara, 1980; Chien et al., 1987).

To accelerate and improve the contact between plant roots and fertilizer P, fertilizer placement was advised. Such advice was usually based on the knowledge that P is highly immobile in most soils, because of its low solubility and its often high degree of retention in the soil. In practice, placement has often proved to be more efficient than broadcast application (De Wit, 1953).

In spite of the improvements that have been made in fertilizer technology and fertilizer application methods, the fractions of fertilizer P recovered by the plants are commonly still low. The low recovery is usually explained as resulting from fixation of fertilizer P in the soil (Russell, 1973; Ball-Coelho et al., 1993).

P fixation has received much attention and research has been concentrated on the various aspects of this subject. For instance, studies were made of:
- P-fixation mechanisms;
- methods to determine the P-fixation capacity of soils;
- methods of fertilizer application on soils low in available P and high in P-fixation capaci-

ties;
- methods to increase the availability of native and fertilizer P and to reduce the P-fixation capacity;
- methods to select plants or to breed varieties adapted to low levels of available P or capable of utilizing P from sparingly soluble fertilizers, such as phosphate rock.

In Chapters 3.2, 3.5 and 3.6, more attention is paid to these studies.

3.2 SUGGESTED MANAGEMENT OPTIONS FOR P-FIXING SOILS

Recommendations for the management of tropical soils with low levels of available P and high levels of P-fixation capacity were reviewed by Sanchez & Uehara (1980) and Warren (1992). Together, they mentioned eight recommendations. The reasoning behind these recommendations is summarized here.

1. Quenching of the P-fixation capacity by broadcasting large amounts of P and incorporating them in the soil (Young & Plucknett, 1966). This method is known as 'the high-input strategy' and is based on the idea that for optimum crop production, a specific concentration of P is necessary in the solution of a large volume of soil. Large applications of P fertilizers are therefore recommended for soils with high P-fixation capacities.
In field experiments, remarkable initial crop responses and often also residual crop responses over periods of several years have been observed (Kamprath, 1967; Fox et al., 1968). Apparently, the residual fertilizer P is gradually released at rates sufficient to support adequate crop growth. In addition, large applications of P fertilizers indirectly produce beneficial changes in chemical and physical soil properties in highly-weathered soils. Stoop (1974) has found increases in cation-exchange capacity (CEC) and pH in some Hawaiian soils, while an improvement in soil aggregation was found in an Ultisol from North Carolina by Lutz et al. (1966). This high-input strategy requires, however, high capital investments for fertilizers and equipment to incorporate the fertilizers. Since capital is scarce in most small-scale farming systems, these high investments are a major constraint to the implementation of this strategy in many tropical regions.

2. Placing small quantities of P fertilizer in the soil in such a way that in a limited portion of the solum the P-fixation capacity is quenched and a high level of P availability can be maintained. This method is known as 'the low-input strategy' and is supposed to be suitable for small-scale farming systems. The method is based on the propositions that plants recover a relatively large fraction of the fertilizer P when this is placed near the plants (De Wit, 1953), and that plants can be adequately supplied with P when this is applied to only a small fraction of their rooting system (De Jager, 1979). When P fertilizer is placed near the seeds, P is immediately available to the developing seedlings and so stimulates early growth of plants. This 'starter effect' has been observed in many field experiments and plants that had benefitted from this starter effect often produced higher yields.
With equal quantities of fertilizer applied, placement usually resulted in better recoveries in the first growing season than did broadcasting and mixing. Residual effects of placement of a single application have apparently not been studied so far, but repeated placement of small quantities at the beginning of each growing season has been studied in comparison with

broadcasting and mixing large quantities once at the beginning of the first growing season. In an Ultisol with a high P-fixation capacity, a certain quantity of P fertilizer applied in repeated band placements was found to be more effective than in a single broadcast application (Kamprath, 1967). This was not confirmed in studies by Yost et al. (1978) in an Oxisol and by Nyamekye (1990) in an Alfisol.

3. Reducing the P-fixation capacity by applying lime prior to P application. This recommendation has been rather controversial as liming can affect P fixation in different ways. A rise in pH resulting from liming may decrease the reactivity of the adsorption sites (Breeuwsma, 1973) and neutralize exchangeable aluminium (Woodruff & Kamprath, 1965; Bruggenwert, 1972), thus lowering the P-fixation capacity. Further, HCO_3 ions competing with H_2PO_4 ions for adsorption sites (Nagarajah et al., 1968) may also reduce the P-fixation capacity. Alternatively, $CaCO_3$ (Kuo & Lotse, 1972; Salingar & Kochva, 1994) and Ca ions (Olsen & Watanabe, 1957) have the ability to adsorb and precipitate phosphate, and so may increase the P-fixation capacity.
The overall effect of liming differs among soils. Only on acid soils with high levels of exchangeable Al is a decrease in P-fixation capacity to be expected (Sanchez & Uehara, 1980; Smith & Sanchez, 1980). In addition, liming may induce a release of a fraction of the sorbed and precipitated P and thus increase the P-availability. H_2PO_4 ions may desorb (see Chapter 3.5.2), due to displacement by H_2O, OH^- or HCO_3^-, while Al and Fe phosphates will dissolve provided that the activities of Al^{3+} and Fe^{3+} remain in equilibrium with $Al(OH)_3$ and $Fe(OH)_3$ solids respectively (Lindsay & Moreno, 1960). Furthermore, liming may induce other beneficial effects in certain tropical soils, as lime eliminates toxicities of Al and Mn and it supplies Ca and Mg.

4. Reducing the P-fixation capacity by applying silicates. This recommendation is based on the assumption that silicate and phosphate ions compete for adsorption sites. A literature review on Si-P interactions in soils was presented by Adams (1980). In a P-adsorption experiment, $CaSiO_4$ was found to lower the P-fixation capacity (Smyth & Sanchez, 1980). This recommendation hasn't been given much attention in plant nutrition studies.

5. Selecting appropriate P-fertilizers. Fertilizers that slowly release P may reduce the rate of P fixation in the soil and may improve P recovery by plants, as roots may intercept P before being fixed by the soil constituents. From this viewpoint, phosphate rock is recommended as fertilizer. It is assumed that P of sparsely soluble phosphate rock is slowly released in the soil during many years and may eventually become more effective than acidulated phosphate rock (Chien et al., 1987). In addition, phosphate rock is usually cheaper than acidulated phosphate rock and may become more economical in soils with a high P-fixation capacity.

6. Improving physical and chemical soil conditions. Improvement of physical and chemical conditions may result in a higher P recovery or in a better P utilization in plants. This is one of the reasons why the application of organic materials is recommended. A mulch coverage, for instance, provides good physical conditions for mineralization and root activity near the soil surface, especially in tropical soils and so may improve P uptake from the tilled layer of the soil (Ball-Coelho et al.,1993). Organic ions may compete with H_2PO_4 ions and so prevent P

fixation in the soil. Organic manures also supply substantial amounts of essential nutrients and so may improve the utilization of P in plants. They also act as a relevant P source. Organic P is slowly mineralized in the soil and so may act as a major P source for the plant during a growing season. Jungk & Claassen (1986) mentioned the possibility of organic P uptake after hydrolyses by plant produced phosphatase in the rhizosphere.
However, for application of P in excess of the quantity removed by the crop, large amounts of organic material are necessary, which are often not available in tropical farming systems. In addition, organic material may adsorb P (Gerke & Hermann, 1992) and it may induce temporary microbiological immobilization of P. Immobilization depends, among other things, on the properties and activities of micro-organisms, the properties of the organic substrate on which micro-organisms feed, on environmental factors such as moisture, temperature, pH, concentrations of O_2 and nutrients, and materials excreted by micro-organisms. The amount of P immobilized is positively correlated with the quantity and the C/P ratio of the organic substrate (Cole et al., 1978; Chauhan et al., 1979).

7. Selecting cultivars or plant species that are capable of extracting phosphate from soils with very low levels of available P, or that have low P requirements for optimum crop production. Many tropical soils low in available P and high in P-fixation capacity often have high levels of exchangeable Al and low levels of exchangeable Ca. The abilities of plants to utilize slightly available P from such soils and to tolerate high levels of Al seem to be interrelated (Salinas & Sanchez, 1976). Since specific genes seem to regulate the degree of tolerance to Al, plant breeders will probably be successful in making optimal use of the P present in these soils, by developing cultivars that are not hampered by Al toxicity.
Among plant species, differences were found with respect to P requirements both internally (Andrew & Robins, 1969, 1971; Couto et al., 1985) and externally (Fox, 1979). In the future, efforts to select species or cultivars on the basis of these requirements may prove successful. High abilities to withdraw soil phosphates are often associated with root morphology (Jungk & Claassen, 1986) and the existence of host plant-mycorrhiza symbioses (Thompson, 1991).

Other selection criteria can be based on the differential ability of plants to alter certain soil properties in the rhizosphere. Three mechanisms are mentioned.

(I) Plants may absorb non-equivalent amounts of cations and anions and simultaneously maintain electroneutrality by excreting ions, for instance H^+ or OH^- . Through this mechanism, plants can alter the pH and thus affect the availability of P in the rhizosphere. Ionic uptake patterns seem to be genetically controlled and differ considerably among plant species (Van Raij & Van Diest, 1979). In addition, these patterns can be affected by variations in the form in which nitrogen is absorbed. When N is taken up in the form of NH_4^+ or through symbiotic N_2-fixation, uptake of nutrient cations commonly exceeds that of anions, leading to a decrease in rhizosphere soil pH. Alternatively, when N is taken up in NO_3^- form, less cations than anions usually are taken up, resulting in an increase in rhizosphere pH. If it were possible to breed plant species on the basis of their ionic uptake patterns and their ability to change these patterns under influence of variations in type of N nutrition, this would probably open up the possibility of using plant species capable of utilizing sparsely soluble phosphates. Knowledge of these patterns has been successfully applied by Aguilar (1981), who showed in pot trials that the utilization of sparingly soluble basic phosphate rock was favourably affected by the alkaline uptake pattern of certain legumes induced by symbiotic N_2-fixation.

(ii) Plant roots may excrete organic acids (Scheffer et al., 1962; Hoffland et al., 1989) and so increase P concentration in the soil solution within the rhizosphere by ligand exchange and solubilization of P sorbing aluminum and iron sites (Fox et al., 1990; Gerke, 1993), and increase P desorption rate (Gerke 1994).

(iii) Plants produce phosphatase in the rhizosphere (Jungk & Claassen, 1986), especially when they are deficient in P (Helal & Sauerbeck, 1987). Trolldenier (1992) photographed this phenomenon and found the apical root region to be most intensive for phosphatase activity and subsequent solubilization of newly formed calcium phosphate precipitates.

8. Improving the mycorrhizal condition of the soil. Vesicular arbuscular mycorrhizas allow plant roots to explore a larger soil volume and so may enlarge P uptake by plants. The existence of host plant-mycorrhiza is assumed to be especially relevant in soils low in available P. The contribution of mycorrhizas towards P uptake and P recovery and the culture practise to improve the mycorrhizal conditions of the soil are receiving more attention in tropical agricultural management (Thompson, 1991).

3.3 THE PHOSPHORUS CYCLE IN NATURE

The fate of phosphorus in nature is shown in Figure 6. Igneous and sedimentary rocks usually contain small amounts of P minerals. The soils that developed from these rock materials contain phosphorus in minor quantities. In many virgin soils, the total P content ranges from about 100 to 2,000 mg/kg (Black, 1968; Sanchez, 1974). In natural waters and soil solutions, the total P concentration is often as low as about 10^{-6} mol/l. (0.03 mg/l) (Stumm & Morgan, 1970; Taylor & Kilmer, 1980).

In spite of its low solubility, P is steadily withdrawn from solution by plants and by various micro-organisms and is concentrated in their tissues. By biological transformation along the food chain, it is further concentrated in animal tissue, especially in skeletons.

In some environments, animal remains have accumulated and during fossilization phosphorus has been preserved. In the geologic past, sediments of remnants of marine organisms were lifted up in tectonic active regions and have been exposed in several regions of the world. These deposits are known as phosphorites and they form the major phosphorus resources. On islands and coastal rocks that have been frequented by birds, excrement has accumulated. Under arid conditions, the excrement including its phosphorus has been preserved in deposits known as guano, while under humid conditions excrement and underlying rock have reacted with each other to form phosphatized rock.

Phosphorite, igneous apatite and guano are used as P fertilizers or as raw material for P fertilizer manufacture. The application of P fertilizers closes the cycle or at least short-circuits the phosphorus cycle in nature.

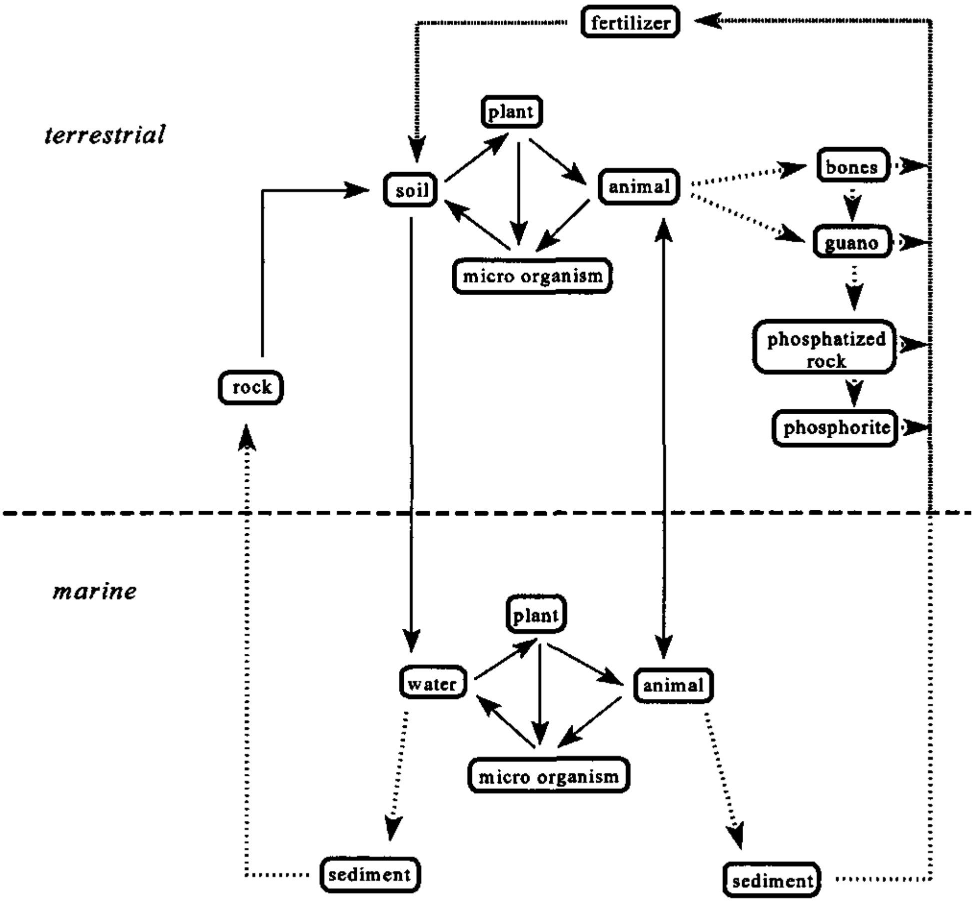


Figure 6. The phosphorus cycle in nature and contribution of P fertilizer application.

3.4 THE PHOSPHORUS CYCLE IN SOILS

In most soils, organic and inorganic P compounds are in a dynamic equilibrium with each other (see Figure 7). Plants and micro-organisms synthesize organic material and so convert inorganic P into organic P. Reversely, the organic material is mineralized biologically and chemically by hydrolysis and oxidation, and so organic P is reconverted into inorganic P. The rates of these conversions, as well as the position of the equilibrium in soils, are regulated by climate, soil properties, plant growth and microbial and animal activities. In agricultural soils, tillage, artificial drainage, fertilizer application and cropping considerably affect these conversions (Anderson, 1980). Mineralization of organic material and release of P from organic sources is presently a topic in soil pollution (Van der Zee & Van Riemsdijk, 1986; Sharpley & Withers, 1994) and plant nutrition studies (Beck & Sanchez, 1994).

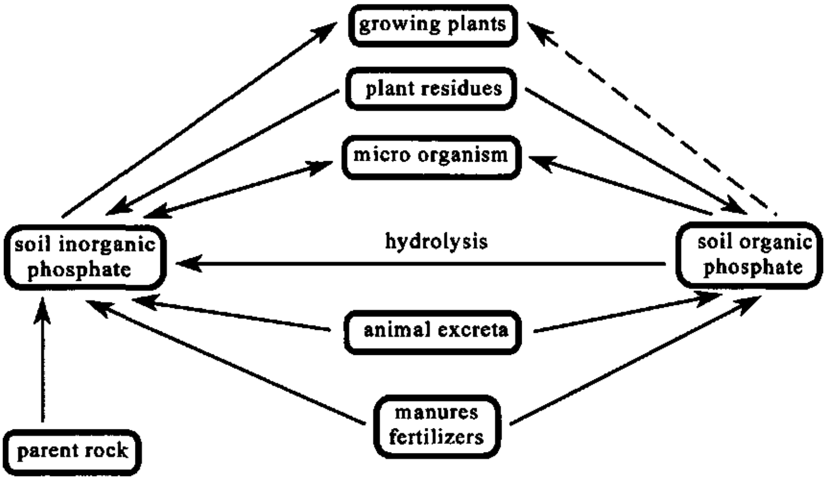


Figure 7. The phosphorus cycle in soils (after Anderson G. 1980)

The major part of phosphorus in soils is present in solid form. Orthophosphate is the predominant phosphorus species in both the organic and inorganic compounds. Identification of P compounds is often complicated. Literature on methods of identification and properties of organic P compounds were reviewed by Anderson (1980). For inorganic P compounds, reviews were presented by Beek & Van Riemsdijk (1979) and by Sample et al. (1980). More recently non-destructive methods for the identification of P compounds have been developed, such as scanning and transmission electron microscopy and X-ray micro-analysis for solid materials. (Henstra et al., 1981; Martin et al., 1988; Salingar & Kochva, 1994) and NMR for liquids (Loughman, 1985). Part of the P in soils occurs in crystalline and amorphous compounds that are often associated with one or more of the following constituents: Ca, Mg, Al, Fe, K, Na, H, OH, F, CO_3 and organic matter. Another part is sorbed on surfaces of clay minerals, hydrous oxides of iron and aluminum, carbonates or complex compounds of organic ion species and Fe^{3+}, Al^{3+} or Ca^{2+}.

Only a small fraction of the P in soils is present in the solution, in the form of $H_2PO_4^-$, HPO_4^{2-} , or of dissolved organic P species, or in the form of complex ionic species associated with cations such as Ca^{2+}, Mg^{2+}, Mn^{2+}, Fe^{2+}, Fe^{3+}, Al^{3+} or Zn^{2+}, or it may be sorbed on surfaces of dissolved organic or inorganic compounds (Olsen & Khasawneh, 1980; Taylor & Kilmer, 1980).

3.5 FATE OF FERTILIZER P IN SOILS

3.5.1 Dissolution of P fertilizers

Apatite is often the dominant P mineral in deposits and rocks used for P-fertilizer manufacture. The solubility products of hydroxyapatite, $Ca_5(PO_4)_3(OH)$, and of Fluorapatite, $Ca_5(PO_4)_3F$ are as low as $10^{-113.7}$ and $10^{-120.86}$, respectively, at 25 °C and 0.1 M PA (Lindsay & Moreno, 1960; Sillen & Martell, 1964). Complete acidulation of apatites yields monocalcium phosphate monohydrate (MCP), $Ca(H_2PO_4)_2.H_2O$ which is highly soluble and the main P compound in superphosphate fertilizers. When MCP dissolves in water, the final P concentration in solution is not controlled by the solubility product of MCP only, but also by the solubility product of more basic calcium phosphates. When MCP dissolves, dicalcium phosphate, $CaHPO_4.2H_2O$, precipitates, while H^+ and P concentrate in the solution, the latter especially in the form of H_3PO_4. If, due to a large application of superphosphate or drought, the amount of MCP is large in comparison with the amount of water in the soil, a strongly acid and highly concentrated solution develops (Lindsay & Stephenson, 1959).

Other P fertilizers, such as ammonium phosphate, potassium phosphate and poly-phosphates, are readily soluble in water (Lindsay, 1979) and do not easily form secondary and tertiary phosphates and so do not show the degree of H^+ production during dissolution as observed with MCP.

3.5.2 Reactions between fertilizer P and soil constituents

When phosphate fertilizers are applied to soils, the phosphate dissolves and starts reacting with various soil constituents. In most soils the reactions can be of chemical, physical or biological nature and they often proceed simultaneously under field conditions, so that the nature of the reactions and the relative importance of each of the reactions are difficult to determine. Whatever the nature of these reactions, the result is always that fertilizer P is retained by soil constituents.

P retention has been studied thoroughly and there is extensive literature on subjects such as the ability of soils or individual soil constituents to retain P, the reaction mechanisms involved in the retention, and factors such as moisture and temperature, regulating the rate of the retention and affecting the forms in which P is retained. Literature on these subjects was reviewed by Beek & Van Riemsdijk (1979) and by Sample et al. (1980). Reviews focused more on tropical soils were presented by Sanchez & Uehara (1980). In the last decade, attention has been paid to modelling the P processes in the soil, such as dissolution and diffusion (Kirk & Nye, 1985, 1986), sorption and desorption (Barrow, 1983, 1986; Van Riemsdijk et al., 1984, Lookman et al. 1995, Freese et al. 1995), and transport (Van der Zee & Bolt ,1991).

When P is applied to soils in liquid form, the P concentration in the soil solution usually decreases rapidly at first, and subsequently declines slowly over a period of several months (Barrow & Shaw, 1975). As a consequence, the amount of P retained by the soil constituents increases with time, rapidly at first and subsequently more slowly (Black, 1942; Van Riemsdijk et al., 1984). The initial rapid decrease in concentration can be ascribed mainly to adsorption, which reaches completion in a few hours, while the slow decline is ascribed to several processes, such as precipitation (Van Riemsdijk & Lyklema, 1981; Martin et al., 1988), crystal growth (Stumm & Leckie, 1971), renewal of adsorption sites by rearrangements and diffuse lattice penetration of adsorbed and precipitated P (Beek, 1979; Barrow, 1983; Van Riemsdijk et al.,1984), and microbial immobilization (Chauhan et al., 1979). Furthermore, in porous soils, diffusion of P between and into soil aggregates is a slow process and, consequently, the retention on these inner surfaces takes time, which is another reason for the slowness of the decline of the P concentration in the soil solution (Muljadi et al., 1966; Willet et al., 1988).

Soil constituents involved in the retention of P are present in solid and liquid form. If present in liquid form, they are concentrated mainly in a diffuse double layer or in a Stern layer of charged solids, while in the bulk solution they often occur in low concentrations. Retention of P will therefore take place preferentially near and on the surfaces of solid soil constituents.

Single coordinated (M-O-H) groups situated on edges of clay minerals, on hydrous oxides of Al and Fe and on humic substances, or exposed Ca ions on calcium carbonates, are mainly responsible for adsorption of P on surfaces. At low pH, (M-O-H) groups associate protons and so change into $(M\text{-}O{<}H/H)^+$ groups, whereas at high pH they dissociate protons and so change into $(M\text{-}O)^-$ groups. The relative distribution of these three species is a function of the pH in the soil solution (Breeuwsma, 1973). Consequently, P retention decreases with increasing pH. Contrary results were noted by Gerke & Hermann (1992). They found an increase in P retention on humic-Fe-surfaces in the pH range of 5.2 to 6.2, which they explained by an increased accessibility of the adsorption sites. Exposed Ca ions adsorb HCO_3^-, OH^- or H_2O groups electrostatically (Kuo & Lotse, 1972). Exchangeable cations such as Al, Fe and Ca species electrostatically held in diffuse double layers also participate in the P retention (Olsen & Watanabe, 1957; Coleman et al., 1960; Gerke & Hermann 1992).

The chemical reactions leading to retention of P are still the subject of study and discussion. Muljadi et al. (1966) suggested that an equivalent adsorption takes place, $H_2PO_4^-$ replacing OH^- and vice versa, and they assumed the adsorption forces to be electrostatic in nature. Many others, for instance Kuo & Lotse (1972) found that a super-equivalent adsorption occurs and assumed an exchange with surface (H_2O) groups. Breeuwsma (1973) found that $H_2PO_4^-$ replaced H_2O groups at low pH and OH^- groups at high pH values, and concluded that these exchanges were in accordance with the behaviour of (M-O-H) groups under varying pH conditions. Most researchers assume the formation of covalent bonds between adsorbed P and (M-O-H) groups, and so consider adsorbed P to be part of the adsorbents (Kafkafi et al., 1967; Kuo & Lotse, 1972). This kind of retention is referred to as chemisorption (Breeuwsma, 1973), metal-bridge bounding (Gerke & Hermann, 1992) or chemical precipitation (Kittrick & Jackson, 1956). Van Riemsdijk (1979), however, used the latter term only for adsorption beyond the adsorption maximum under conditions of supersaturation with respect to one or more metal-phosphates. To avoid ambiguity, the neutral term sorption is often used to indicate physico-chemical processes occurring in diffuse double layers and in Stern layers, and the term precipitation for physico-chemical processes occurring in the bulk solution. Both processes contribute to the P retention.

3.5.3 Movement of fertilizer P in soils.

After having been applied to soils, fertilizer P may move in liquid form or in solid form or be withdrawn from the site of application by plants.

Dissolved phosphate is transported by mass flow (with the flowing soil water) or moves by diffusion (through the soil solution). Since it is retained in most soils, the speed with which it moves is usually considerably slower than that of the soil water. Movement of dissolved salts through soils, by both mass flow and diffusion, has been studied intensively (Bolt, 1979). Movement of dissolved phosphates in soils has been a topic in studies on plant nutrition and soil pollution (Nye, 1968; Mansell et al., 1977; Beek, 1979; Raats et al., 1982; Van der Zee & Bolt, 1991). The total flux of dissolved P in soils is a function of the water flux, the P concentration in the soil solution, the P-diffusion flux and the P-retention capacity of the soil. In turn, the water flux is a function of the hydraulic pressure and of the impedance of the soil. The impedance depends on the geometry of the pores in the soil and it increases with decreasing moisture content. The P-diffusion flux is a function of temperature, moisture content, diffusion pattern of cations flowing in combination with phosphate ions and ion behaviour in diffuse double layers of soil constituents (Olsen et al., 1965).

Due to the low concentration and the low self-diffusion coefficient of P ions in soil solutions, the total flux of dissolved P is often small. Due to the P retention in the soil, the distance over which movement of dissolved P takes place is relatively short (Bhadoria et al., 1991). Under special conditions, however, when a highly soluble fertilizer, for instance triple superphosphate (TSP), is applied to a very porous soil and mass flow proceeds rapidly, relatively large P fluxes might temporarily occur over comparatively long distances. Due to the spatial variability of physical and chemical soil properties dispersion occurs especially at high mass flow rates (Van der Zee & Bolt, 1991)

Part of the fertilizer P is withdrawn from the site of application by plants and is distributed within the plant. A minor part returns after harvest in the form of litter and roots, which means that the fertilizer P becomes part of the organic P fraction in the soil (Beck & Sanchez, 1994).

Another transport mechanism is of a mechanical nature. In soils with a high biological activity, due to the presence of for instance ants, termites, earthworms and groundvoles, in soils that shrink and swell in alternating dry and wet seasons, or in soils that are cultivated, mass transport takes place, so that fertilizer P residues and soil material in which fertilizer P is retained are displaced and are mixed with other soil material.

Where argillation or podzolization occur, and in soils susceptible to erosion, other ways of transport are possible. Fertilizer P attached to clay, organic matter or hydrous oxides of Fe and Al may become displaced from topsoils, and may accumulate in argillic, agric, or spodic horizons of subsoils. In soils susceptible to water erosion, especially sheet and rill erosion, or to wind erosion, retained fertilizer P and residues of previously applied fertilizers are subjected to erosion too. Taylor & Kilmer (1980) and Sharpley & Withers (1994) have reviewed the literature on P losses from agricultural soils by water erosion.

3.6 FACTORS AFFECTING P UPTAKE BY PLANTS.

P is taken up by plants predominantly in the form of $H_2PO_4^-$. The H_2PO_4 ions in the soil solution move towards the roots by mass flow, set into motion by water uptake, or diffusion. Usually diffusion is the main process and, especially in soils with low levels of P, nearly all the P in the rhizosphere moves in this way (Barber, 1980). Marschner (1995) reviewed the ion uptake mechanisms. Within the roots, transport of P takes place along two pathways: 1. along the apoplasm, the intercellular space in the cortex, which is considered to be freely accessible to both water and ions, or 2. along the symplasm, the intracellular space that is separated from the apoplasm by the plasmalemma and in which transport from one cell to another occurs via plasmodesmata. In root tips, transport along both pathways is possible, but as soon as roots are a few days old the intercellular transport is blocked at the endodermis due to formation of Casparian bands, so that only symplasmatic transport will take place across the endodermis. For entering the symplasm, H_2PO_4 ions must pass the plasmalemma. This passage (absorption) requires energy (Higinbotham et al., 1967), which is obtained metabolically from respiration. After having been absorbed in the symplasm, $H_2PO_4^-$ is incorporated to form organic phosphates, for instance adenosine triphosphate (ATP), which also requires metabolic energy, or it is transported to the xylem and subsequently distributed over the entire plant.

By actively absorbing $H_2PO_4^-$, plants deplete the soil solution and so create P concentration gradients perpendicular to the root circumference. Consequently, centripetal diffusion develops and this diffusion continues as long as plants are able to absorb $H_2PO_4^-$ and soils are able to replenish the $H_2PO_4^-$ withdrawn from the soil solution. In as far as this is done by the plant, P absorption is thought to be regulated primarily by the concentration of inorganic phosphate in the symplasm of the root cells (Blasco et al., 1976). De Jager (1979) that this concentration in turn reflected the P-status of the shoot and that it was controlled by redistribution of P from the shoot to the roots.

Replenishment of $H_2PO_4^-$ in the soil solution is regulated thermodynamically. The various P sources in the soil (see Chapter 3.4) release $H_2PO_4^-$ at differential rates. These differences in kinetics justify an arrangement of the P sources according to their reactivity. On the basis of these variations in reactivity, Larsen (1967) distinguished between soluble, labile and non-labile P forms.

At low concentration, the P-uptake rate was found to be a function of the P concentration in a culture solution, which is shown graphically in Figure 8.
A Michaelis-Menten equation satisfactorily describes this relation for P concentrations up to 50 μmol/l. This equation can be written as follows:

$$I = I\,max * (C - C\,min) / (Km + (C - C\,min))$$

in which: I is the P-uptake rate per unit root length, in pmol/cm sec. C is the P concentration in solution, in μmol/l. I max is the maximum P-uptake rate per unit root length, in pmol/cm sec. Km is the Michaelis-Menten constant, in μmol/l. C min is the minimum P concentration to which the solution can be depleted, in μmol/l.

The following data on P uptake for maize plants were presented by Barber (1979): I max = 0.4 pmol/cm sec, Km = 3 μmol/l, C min = 0.2 μmol/l (0,006 mg/l). When these values are substituted in the Michaelis-Menten equation, the following relationship is obtained.

$$I = 0.4 * (C - 0.2) / (3 + (C - 0.2))$$

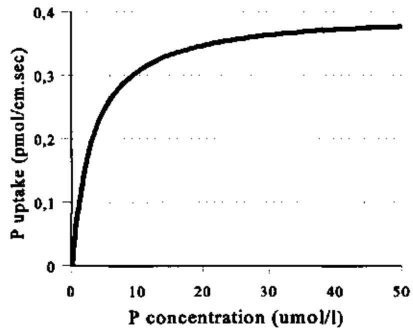


Figure 8. Relationship between P concentration in solution and net P influx for 18 day old corn plants (after Barber, 1979).

At P concentrations higher than 50 μmol/l, however, absorption rates may exceed the value of I max, so that simple Michaelis-Menten kinetics assuming saturation of enzyme activity cannot be applied (for a further discussion of this phenomenon, see Olsen & Khasawneh, 1980). Above P concentrations of 50 μmol/l, the following uptake rates for roots of maize plants were recorded: 0.40 and 0.48 pmol/cm sec, at C = 100 μmol/l (Jungk & Barber, 1974); 0.36 and 0.48 pmol/cm sec, at C = 500 μmol/l (De Jager, 1978); 0.40 and 0.56 pmol/cm sec, at C = 1,000 μmol/l (Jungk & Barber, 1974). Of each pair, the first number refers to conditions in which P was supplied to a complete root system and the latter one to conditions in which only a limited fraction of the roots was actively involved in P uptake.

Both the diffusion of $H_2PO_4^-$ from the soil to the roots and its uptake by plant roots are influenced by several factors. The various factors affecting diffusion were mentioned in Chapter 3.5.3. Some factors affecting absorption, for instance root morphology and root activity, are largely genetically and partially environmentally controlled. Root-morphology characteristics such as root radius, root length and the presence of root hairs vary among species and even among varieties (Nielsen, 1978), and are likely to affect the rate of P absorption per unit root mass (Jungk & Claassen, 1986). Theoretically, plants having thin roots densely covered with root hairs are better adapted to grow on soils with low levels of available P than are plants having thick roots without root hairs, provided that the abilities of the roots to absorb P are equal per unit of root surface (Van Noordwijk & de Willigen, 1979). Whether plant species naturally selected for growing on P-deficient soils have, indeed, developed finer root systems does not seem to have been confirmed as yet. However, when grown on P-deficient soils, certain species develop thinner roots or larger root hairs than when grown on soils to which P was applied (Bhat & Nye, 1974; Powell, 1974). Root activity measured in terms of maximum P-uptake rate per unit root length was found to vary widely among species (Jungk, 1975). Even among maize varieties, considerable variations were found in values of I max, Km and C min (Nielsen & Barber, 1978). Probably differences in phosphatase activity, production of root exudates and mycorrhiza symbioses also contribute to these variations (see Chapter 3.2).

Other factors affecting absorption, such as temperature, soil-water potential, soil aeration, mechanical impedance (reviewed by Drew, 1979) exert their influence on root metabolism and thus affect the P-uptake rate. The optimum temperature range for maize growth is 20 - 30 °C (Brouwer et al., 1973). Water stress can strongly impede root functioning. Hence, when water stress develops, young roots will suberize to protect themselves against desiccation. In such conditions, root functioning probably continues normally, as suberization of the endodermis was found to have little effect on the absorption and radial movement of $H_2PO_4^-$ in maize roots (Ferguson & Clarkson, 1975). Under prolonged water stress, however, cortical cells loose water and collapse, leading to a reduction in absorbing root surface area and eventually resulting in damage to the symplasm (Clarkson et al., 1968). Additionally, shrinkage of roots gives rise to the formation of air-filled gaps between root surface and surrounding soil, resulting in an interruption and possibly in a strong reduction in water flow and in $H_2PO_4^-$ diffusion to the roots.

$H_2PO_4^-$ uptake is also affected by variations in the ionic composition of the soil solution. The various interactions of P with other elements were reviewed by Loneragan (1979) and Adams (1980). Only the effect of Ca on P uptake will be reviewed here. Ca plays an important role in membrane behaviour (Marschner et al., 1966) and its presence in the rhizosphere is essential for normal root functioning.

Ca and P show an absorption synergism. Ca stimulates P uptake (Hyde, 1966) and P stimulates Ca uptake (Bar Yosef, 1971). Robson et al. (1970) found that, in culture solutions, a stimulation exerted by Ca on the P uptake was more pronounced at a P concentration of 0.2 μmol/l than at 5 μmol/l. At the lower concentration, the P uptake more than doubled. These findings probably indicate that the synergistic effect of Ca is of importance especially in soils low in available P. So far, this effect has been tentatively attributed to the role Ca ions play in the behaviour of P "carriers" or to the influence Ca ions have on the neutralization of electronegative adsorption sites leading to an improved accessibility to root cell membranes by H_2PO_4 ions.

Alternatively, Ca may impede P uptake. When the amount of Ca supplied by mass flow exceeds the amount absorbed, Ca^{2+} will accumulate at the root surface. If Ca and P ions then precipitate, any further accumulation of Ca will decrease the P concentration in solution and Ca may eventually, when this falls below a critical level, reduce the P-uptake rate. Although the occurrence of such a phenomenon is postulated (e.g. Jakobsen, 1979), there is still little evidence for the precipitation of calcium phosphates at the root surface or indications of reduction of P-uptake rates.

Whether or not plants growing on tropical soils with low levels of P availability and high P-fixation capacities can be adequately supplied with P will depend primarily on a few plant-, soil- and environmental factors. The minimum P concentration (C min) to which plants can deplete culture solutions varies among species from 0.01 μmol/l to 0.4 μmol/l (Barber, 1980) and among certain maize varieties from 0.04 μmol/l to 0.12 μmol/l (Nielsen & Barber, 1978).

Since P concentrations in the soil solutions of many tropical soils are at, or probably even below, the detection limit of P, which is about 0.06 μmol/l (Fox, 1979), it can be expected that several plant species will not be able to absorb P from these soils or to absorb it at a sufficient rate from the soil solution. In many soils, the P concentrations in soil solution vary between 0.6 μmol/l and 2.6 μmol/l (Barber et al., 1963). As can be observed in Figure 8 or calculated from the equation above, maximum P-uptake rates (I max) will not be attained at these concentrations, so that I max is not a plant factor that limits the P-uptake rate. However, near freshly applied P fertilizers, I max probably becomes the rate-limiting factor, as at fertilizer application sites high P concentration in soil solution might occur temporarily.

Diffusion of P to the roots will often affect the P-uptake rate. In many tropical soils, due to a low native P concentration in the soil solution and fixation of fertilizer P, diffusion fluxes are very low (Bhadoria et al., 1991). Often, these fluxes are further reduced by low water potentials (Gahoonia et al., 1993) which develop during dry periods frequently occurring in growing seasons. These three factors viz. low native P concentrations, fixation of fertilizer P and low water potentials likely dominate these fluxes and so may largely determine the P-uptake rates. Other possible rate-limiting factors are those which regulate desorption, dissolution, decomplexation, or mineralization of organic phosphates and so control the release of P from soil constituents. In soils low in labile P, the slow release of P is likely to limit the P-uptake rate. Literature on release of P from soils was reviewed by Olsen & Khasawneh (1980) and on release of P from fertilizer residues by Barrow (1980) and Warren (1992).

Summarising, the P-uptake rates may be limited by the inability of plants to absorb P or, in other words, by a low P concentration in the soil solution. Furthermore, P uptake may be limited by low P-diffusion fluxes, or by low rates of P release from soil constituents. Around fertilizer granules, P uptake rates are probably temporarily limited by I max.

4 CONCEPT OF P FIXATION AND DEFINITIONS

4.1 CONCEPT OF P FIXATION IN LITERATURE

Since, in soil fertility and soil chemistry, the concept 'phosphate fixation' has been approached in different ways, the term phosphate fixation has been given diverse meanings and is therefore an ambiguous term.

In soil fertility, P fixation is generally interpreted as the process in which easily-soluble fertilizer phosphates are transformed into such insoluble forms that their uptake by plants is hindered or even blocked. Slight increases of available P, low recoveries of fertilizer P and small initial and rapidly-declining residual yield responses are characteristic phenomena for the occurrence of fertilizer P fixation in a soil.

In soil chemistry, P fixation has often been interpreted as the process in which P present in liquid form is almost irreversibly adsorbed by or precipitated on solid soil constituents (Sanchez and Uehara, 1980). Part of the precipitated and adsorbed P dissolves and is desorbed, respectively, when the soil solution is depleted of P or when it is displaced by a solution that is free of P or otherwise differs in ionic composition. This portion of the soil P is readily available to plants and is designated by terms such as extractable P, exchangeable P, reversible P, labile P and available P. The other part of the soil P will dissolve or be desorbed only at a very slow rate, and it is assumed that this part is not readily available to plants. This rather insoluble part is designated by terms such as non-extractable P, non-exchangeable P, irreversible P, non-labile P, unavailable P, stable P, occluded P and fixed P.

4.2 CONCEPT AND DEFINITIONS AS USED IN THIS STUDY

P fixation:

Following Chapter 4.1, P fixation can be considered as a process in which P is adsorbed and precipitated on the soil constituents and eventually becomes almost irreversibly retained.

The process proceeds in two phases. In the first, fast phase, which is assumed to last a few days, P is adsorbed and precipitated on the soil constituents. In the second, slow phase, which continues at a decreasing rate, the retained P is built into the soil matrix by diffusion into soil aggregates and rearrangement of the adsorption sites.

For agricultural practice, P fixation becomes a problem when fixation proceeds so rapidly that the plant response to P application is hindered or even blocked. This is expressed by phenomena such as a small initial crop response and no, or rapidly decreasing, residual crop responses and corresponding low fertilizer P recoveries in the crop. Eventually, the fertilizer P might be transformed into soil P with properties and behaviour similar to those of the native soil P of a soil low in plant-available P.

Therefore, P fixation is defined here as a process which starts with a rapid adsorption and precipitation of fertilizer P on soil constituents and eventually results in the transformation of fertilizer P into soil P, with properties and behaviour similar to those of the native soil P. Evidently, in agricultural practice, P fixation can only be a problem on soils with a low P status.

The fixation process is assumed to be regulated with respect to its rate and extent by:
- soil-chemical characteristics; such as the P status of the soil and the amount and reactivity of iron and aluminum oxyhydroxides in the soil;
- soil-physical conditions; such as the moisture status and temperature of the soil;
- fertilizer application practice; such as the type of fertilizer, application rate and fertilizer distribution within the soil;
- plant root - soil interaction and microbial activity.

In the qualitative sense, P fixation proceeds rapidly if the P status of the soil is low, if large amounts of reactive iron and aluminum oxyhydroxides are present in the soil, if the soil is moist and temperature high, if large amounts of highly-soluble P fertilizer are applied and if P fertilizer is finely and homogenously distributed in the soil. Plants and micro-organism interfere in the P-fixation process, as they withdraw P from the soil solution and may excrete organic ions.
Unfortunately, no mechanistic and deterministic model is yet available that includes all these complex factors and interactions and is parameterized for all factors.

<u>P-fixation capacity</u>
The P-fixation capacity of a soil can be defined as the ability of a soil to change fertilizer P rapidly into soil P that behaves similarly to the native soil P with respect to plant availability. This definition implies that a plant or crop is used as test medium.
Usually, however, the P-fixation capacity is determined in a chemical way. In the latter case, a certain amount of P in liquid form is added to a soil suspension and, after a certain reaction time, the amount of P remaining in solution is measured, so that the amount sorbed by the soil constituents can be calculated. Since at least a fraction of the sorbed P may return into solution and will therefore be available to plants, the fixation capacity determined in this manner can be expected to be an overestimation of the real P-fixation capacity.
It should therefore be referred to as <u>P-sorption capacity</u>. Sometimes, the term <u>P-retention capacity</u> is used instead of P-sorption capacity. From now on in this study, the terms P sorption and P-sorption capacity are used. The sorption is a result of physico-chemical reactions and, if not suppressed, some biological processes might be involved. To indicate the quantity-intensity relationship the term <u>P-buffer capacity</u> is used occasionally.

Since P sorption is affected by many factors, the conditions under which the P-sorption capacity is measured should be carefully described. Moreover, since the level of P sorption is positively correlated with P concentration in the soil solution, the P-sorption is often measured for several P concentrations. From the data obtained, sorption curves are drawn from which the P sorption can be read or calculated for various P concentrations. As the curves incline with increasing P concentration, it is sometimes supposed that a maximum sorption will be attained at a level above the highest P concentration employed. This maximum P-sorption capacity can then be calculated. This is done for instance when it is assumed that the curve can be described by a Langmuir equation. A different approach is to measure the P sorption at a standard concentration, the <u>'Standard P Requirements' '(SPR)'</u>. Often, the standard P concentration of 0.2 mg/l as proposed by Juo and Fox (1977) is used (Warren, 1992). Ozanne & Shaw (1968) found a final P concentration of 0.2 mg/l (6.5 μmol/l) to be the critical level at which 95 percent of the maximum yields of most crops can be obtained. For comparing different soils on the basis of their SPR, the following P sorption scale was proposed by Juo and Fox (1977): SPR (mg/kg) < 10 (very low); 10-100 (low); 100-500 (medium); 500-1,000 (high); > 1,000 (very high). Warren (1992) referred to this scale.

P availability

The P availability in a soil is a measure of the degree to which P is available to a plant. Soils in which the P availability is high are able to supply P in sufficient amounts and at a proper rate so that plant growth and crop production are not limited by P deficiency, whereas in soils where the P availability is low, this requirement cannot be met so that, due to P deficiency, plant growth is hampered and crop yields are reduced. Since many factors, for instance the chemical nature of the P compounds in soils and in fertilizers, the P-sorption capacity of a soil, the water potential in a soil, and plant-root characteristics, regulate P availability and determine its level, the P availability in a soil is not constant.

To estimate the amount of P in a soil that is available to plants, various chemical extraction methods have been developed. The extractants vary in composition from de-ionised water to rather concentrated solutions that are either acid, neutral or alkaline in nature. Each solution extracts a fraction of the total P present in a soil. This extractable P fraction is often referred to as 'the available-P fraction'. The amount of P extracted in a relatively short time from a soil sample is determined by the chemical composition of the solution and by the chemical characteristics of the soil. The actual amount of P in a soil available to a crop depends on chemical, physical and biological factors and on the manner in which these factors vary in the course of a growing season. Consequently, the extractable-P data themselves have limited value. When correlated with crop yields, however, they have often been found to be useful parameters for estimating P availability in a certain soil for a certain crop and for assessing the amount of P fertilizer that should be applied to obtain optimum yields.

Recovery of fertilizer P

Recovery of fertilizer P is defined as the absorption of applied fertilizer P by plants. A frequently used method for measuring the P recovery is based on the assumption that the quantity of P absorbed by plants from a fertilized plot in excess of the quantity absorbed from a control plot is derived entirely from the fertilizer. The fraction recovered over a certain period of time is calculated with the equation:

$$\text{P recovered} = \{\text{P absorbed } (+\text{P}) - \text{P absorbed } (-\text{P})\} / \text{P applied}$$

where: +P and -P refer to P-fertilized plots and non-fertilized plots, respectively.

Since, under field conditions, the validity of this assumption cannot be proved, the P recovery thus calculated is usually referred to as the apparent P recovery. Estimates of P recovery are often calculated from the amounts of P recovered in the harvested material, for instance in grain. When information is available on the distribution of P over the various plant components, the quantity of P recovered in the harvested material can be used to calculate the total P recovery.

The apparent P recovery may be either higher or lower than the real recovery. It is higher when plants growing on P-fertilized plots absorb more native soil P than plants growing on non-fertilized plots. This might occur in soils with a low availability of native soil P. In such soils, root growth is stimulated by fertilizer P, both within and beyond the sphere affected by the fertilizer (Goedewaagen, 1942). Since a dense root system is capable of absorbing more native soil P, it is conceivable that plants growing on fertilized soil absorb more native soil P. When this priming effect occurs, the apparent P recovery will overestimate the real P recovery.

On the other hand, it can be reasoned that a priming effect might be small or even negative. In the latter case, instead of an increase in uptake of native soil P, a decrease might result from P-fertilizer application. In portions of soil immediately below the P fertilizer, Goedewaagen (1942) observed a higher root density than at some distance above and below the fertilizer. Roots growing in a portion of the soil immediately surrounding fertilizer granules might absorb P at a rate close to the maximum P-uptake rate, whereas roots growing in other parts of this soil might absorb P at a very slow rate. This is particularly true for soils in which the availability of native soil P is low and the P concentration in the soil solution is close to the minimum concentration at which P uptake is assumed to be possible. If those roots that grow in the portion of the soil affected by the fertilizers are capable of meeting the P requirements of the plants, it is to be expected that roots growing in unaffected portions of the soil will make only a minor contribution to the P nutrition of the plants. Under such conditions, a priming effect might be non-existent or even negative. In the latter case, plants absorb less native soil P from a fertilized than from a non-fertilized soil. In such situations, the apparent P recovery will underestimate the real recovery of fertilizer P.

Utilization of phosphate by plants

The efficiency of P utilization by plants is usually described quantatively as the ratio of plant mass produced and P mass absorbed. Utilization may refer to a whole plant or to the marketable plant components. In the present study, it is defined as the ratio of grain mass produced and the P mass absorbed in above-ground plant components, which is given by the equation:

Efficiency of P utilization = grain yield (kg or kg/ha)/P in plant (kg or kg/ha)

This equation can be used for calculating the efficiency at which native soil P is utilised and in an adapted form for calculating the efficiency at which fertilizer P is utilised. If the efficiency of utilization of native soil P is independent of P application and if the quantity of P absorbed in above-ground plant components from a fertilized plot in excess of the quantity absorbed from a control plot is derived entirely from the fertilizer, then the efficiency of utilization of fertilizer P is calculated with the equation:

Efficiency of fertilizer P utilization = {grain yield (+P) - grain yield (-P)} / {P in plant(+P) - P in plant(-P)}

where: +P and -P refer to P-fertilized plots and non-fertilized plots, respectively.

The efficiency of utilization of native soil P can be low under conditions of very low or very high P availability. In the first case, the amount of absorbed P is so low that only or mainly vegetative plant components are formed. In the second case, growth factors other than P limit grain yield, so that P accumulates in the plant in excessive quantities.
For analogous reasons, the efficiency of utilization of fertilizer P can be low when the quantity of fertilizer P absorbed is very small due to a low P application rate or to fixation of fertilizer P, or when it is very large because of an excessive P application.

5 DESIGN OF THE RESEARCH

5.1 INTRODUCTION

When considering the physical conditions and farm-management practice in the survey area (Chapter 2) and when reviewing the recommendations for dealing with P fixation thus far (Chapter 3.2) from both a soil-scientific and an economic viewpoint, it seems that fertilizer application methods based on the low-input strategy are most promising for the soils of South West Kenya.

The high-input strategy, namely quenching the P-fixation capacity by working large amounts of P fertilizer into the soil or reducing the P-fixation capacity by incorporating lime or silicates into the soil, requires investments that are assumed to be unjustifiably high. In addition, since the pH-water values of most soils in the survey area were found to lie between 5 and 6, which is probably too high to raise expectations on the effects of lime and too low to justify assumptions of strong competition between silicate and phosphate ions in their reactions with soil constituents, there is no scientific basis for application of lime or silicates. Other recommendations, such as improving soil-physical and chemical conditions by application of organic matter, selecting cultivars adapted to low native P availabilities and improving the mycorrhizal condition of the soil, were not investigated in the trials for the following reasons: the physical conditions of the soils were assumed to be rather good; organic matter was not available in large amounts; hybrid maize adapted for the Kisii area was available, and improving the mycorrhizal condition was too ambitious to incorporate in the study.

In the low-input strategy, it is assumed that proper crop production on strongly P-fixing soils can be obtained when only a small portion of the solum is fertilized. It is then assumed that, in the limited quantity of soil affected by fertilizer, the P-fixation capacity is quenched, resulting in P concentrations in the soil solution that exceed those at which optimum P nutrition of crops is guaranteed. Due to the presence of a P-buffer capacity, it is further assumed that these high levels of P concentration will be maintained over an extended period, such as a growing season.

The low-input strategy gives rise to the following academic questions:
- How can the P concentration in the soil solution surrounding the fertilizer be controlled to allow P uptake to proceed at an optimum rate, considering the fact that P concentrations should not be raised above the concentration at which the P uptake rate is at a maximum (C max), and that they should not fall below a critical concentration and certainly not below a minimum concentration (C min) (Chapter 3.6)?
- What should be the size of the sphere in the solum affected by fertilizer granules to enable roots growing in this sphere to absorb sufficient fertilizer P?
- Which methods are available to avoid or delay the fixation of fertilizer P in the soil?

Before the low-input strategy is to be recommended, the following practical questions should be answered as well:
- How much P fertilizer should be concentrated to sufficiently quench the P-fixation capacity

of the soil immediately surrounding the fertilizer?
- At what distance from seeds or plants should the fertilizer be placed.
- At what depth in the solum should the fertilizer be placed?
- Should the fertilizer be concentrated in one location or split over several locations near the plant?
- Should the fertilizer be concentrated in a single application or be distributed over several applications?

To answer these questions, insight is required into the major factors that control P fixation and the availability of fertilizer P and thus its recovery by plants. It is also important to know in which way these factors are affected by characteristic properties of fertilizers, soils, plants and climate. Basically, the fertilizer phosphate - soil - maize crop interactions are important.

5.2 OBJECTIVES

The overall aim of the study was to improve our understanding of the fertilizer phosphate - soil - maize crop interactions, and thereby to increase the maize yield response to phosphate fertilizer and to increase the recovery and utilization of fertilizer P in tropical soils with low levels of available P. More specifically, considering the questions formulated in Chapter 5.1, the objectives were as follows:
- to analyze and describe the P status in dominant soil types of the Kisii area and to relate this status to parent material and soil type;
- to study the compositional changes of triple superphosphate fertilizer and fertilizer P transport and sorption in various soils under field conditions;
- to test the efficacy of various methods of fertilizer P application with respect to initial and residual plant responses;
- to assess the short-term (one growing season) and mid-term (three growing seasons) plant recovery of fertilizer P for various soils; and
- to establish a basis for improved recommendations of P fertilizer application with emphasis on the low-input strategy and using the high-input strategy as a reference.

An integrated study involving laboratory and greenhouse experiments in the Netherlands and extensive field trials in Kenya was judged most appropriate for satisfying the objectives mentioned above.
For the determination of the P status, it was decided to combine soil characteristics such as: total P, available P and P-sorption capacities measured in the laboratory (Chapter 6.7) with plant growth characteristics measured in preliminary pot experiments in the greenhouse and in extensive trials in the field. The data on the P status were related to parent material and soil type on the basis of the results of the multidiciplinary project in pedology in Kenya (Wielemaker & Boxem 1982).
The compositional changes of fertilizer P were studied under field conditions and monitored with optical microscopy, X-ray diffraction, scanning electron microscopy and X-ray analyses. Transport and sorption of fertilizer P was followed under field conditions by measuring the changes in total and available P in the soil.
The efficacy of the various methods of fertilizer application was tested in field trials. Plant

response was monitored during three seasons. P utilization was determined and fertilizer P recovery in the plant was followed over three seasons by extensive analyses of plants and plant components.
Recommendations for P fertilizer application were based on the plant responses, P utilization and P recovery and on the farm management practice in the small-scale farming system.

5.3 JUSTIFICATION OF EXPERIMENTAL TREATMENTS IN THE FIELD STUDY

5.3.1 Type of P fertilizers, test crop and agricultural practice.

At the time of the trials (1977 to 1979), valuable deposits of phosphate rock had not yet been discovered in Kenya and those present in Uganda (Tororo phosphate) and Tanzania (Minjingu phosphate) were not available in Kenya. A preliminary study was carried out in the area bordering Lake Victoria, where geologically similar deposits occur as in the Tororo area. Indeed, soils rich in native P were found, but P concentrations were too low for exploitation as fertilizer. The highest P levels were found in the crater centre of the extinct Rangwe Volcano near the village of Rowo. This 'Rowo' soil was used on a small scale in the trials.

Granulated triple superphosphate was chosen because this is the major P fertilizer employed in Kenya and it is usually for sale in the town of Kisii. Because maize is the major food crop in the survey area, and is grown on almost every farm, this crop was chosen as a test crop in the trials.

As farmers are used to sowing maize in holes made with a stick or small hoe (jembe) in previously tilled soil and to applying the scarce cow dung together with the seeds in these holes, and considering the fact that the practice of concentrating fertilizers in holes is in line with the low-input strategy, it was decided to lay the emphasis in this study on methods in which seeds and fertilizers are placed in holes, either together in one hole or in separate holes near each other.

5.3.2 Methods of P fertilizer application

When P fixation proceeds rapidly, fertilizer P applied at planting may become fixed before plants have matured or even before seedlings have become established. To cope with rapid P fixation, three possibilities were considered:
- split applications of P fertilizer during a growing season;
- methods to delay P fixation;
- methods to improve the conditions for fertilizer P uptake.

5.3.2.1 *Split applications of P fertilizer during a growing season*

Top-dressing during the growing season in strongly P-fixing soils is likely to result in fixation of fertilizer P just below the soil surface, which is an unfavourable zone for root growth. Incorporation or placement at some depth below the soil surface is rather laborious and usually leads to root damage. Foliar applications are expected to be ineffective because of frequent rain showers, which wash the sprayed fertilizer from the leaves, while, in a preliminary field experiment, application of triple superphosphate granules in the whorl of the maize plants was found to cause foliar damage, even when a single granule was applied. Hence, split application was not included as treatment in the trials.

5.3.2.2 *Methods to delay P fixation*

Since the split application methods did not show much promise, it was decided to concentrate efforts on the development of methods through which the fixation of freshly added fertilizer P could be delayed. Local cow dung, sewage sludge or soil ('Rowo' soil) were used as a mantle to prevent immediate contact between the triple superphosphate granules and the soil. When fertilizer and soil are kept apart, it takes more time for the dissolved fertilizer to reach the soil. The length of the period over which the fixation of fertilizer P is delayed increases with the thickness of the layer of material used for protective covering. In addition, these materials may act like a buffer in that, by sorbing a part of the fertilizer P and by neutralizing the H ions, they reduce the reactivity of the highly concentrated and strongly acid solution which develops upon dissolution of the triple superphosphate and during conversion of $Ca(H_2PO_4)_2.H_20$ into $CaHPO_4.2H_20$.

Cow dung, sewage sludge and 'Rowo' soil were chosen because of their high contents of extractable P, thereby quaranteeing a low capacity for fixing fertilizer P, and because application of these materials fits in the low-input strategy. Moreover, cow dung and sewage sludge possess four additional characteristics enabling them to delay or reduce the fixation of fertilizer P in soil. These characteristics are:

1. A portion of the fertilizer P may be sorbed by the organic matter fraction of the cow dung and sewage sludge, or may be incorporated in microbial tissue. In the course of a growing season, this sorbed and incorporated P can be released due to mineralization of organic matter, allowing plant roots developing in the cow dung or sewage sludge to absorb the P before it reaches the surrounding soil.

2. During mineralization, the micro-organisms may produce organic acids, whose anions compete with phosphate ions for adsorption sites and in reactions with ionic species of Fe and Al (Nagarajah et al., 1968). When such acids are leached from the cow dung and sewage sludge, the P-sorption capacity of the soil immediately surrounding these materials may be reduced whilst the anions of the acids persist.

3. Well-decomposed cow dung and sewage sludge are finely-structured spongy materials that retain more moisture at field capacity (pF=2) than the surrounding soil (Table 1). Due to differences in moisture-retention characteristics, the water flux in the cow dung and sewage sludge will be different from that in the soil. This might affect the leaching of fertilizer P from cow dung and sewage sludge. If rain falls after a dry period in which both soil and cow dung or sewage sludge have dried out, the rainwater percolates rapidly through the many relatively large interaggregate pores, which are characteristic of the very fine, granular soils of the survey area. When this water reaches the site of the fertilizer, the cow dung or sewage sludge

absorbs and retains more water than the soil. Consequently, the water flux is retarded and directed towards the moisture-attracting cow dung and sewage sludge.
When rainfall is light, the water absorption by the cow dung or sewage sludge may lead to the emptying of inter-aggregate pores of the immediately surrounding soil. This may happen even before the cow dung or the sewage sludge attains a moisture content corresponding with that of field capacity. The flux of water towards the cow dung or the sewage sludge then leads to a moistening, but not a leaching, of these materials.
When rainfall is heavy, the moistening will be followed by leaching and eventually by a removal of fertilizer P from cow dung or sewage sludge. The extent to which the water flux in cow dung and sewage sludge differs from that in soil under saturated conditions, depends on the differences in pore-size distribution between these protective materials and the soil. Leaching of fertilizer P from these materials may occur only temporarily, as in the highly permeable soils the emptying of pores is likely to start soon after rainfall has stopped.

4. Since both cow dung and sewage sludge are well-structured materials containing substantial quantities of essential nutrients, their presence in the soil may affect the rooting pattern of plants. If, in these manures, roots branch more profusely than in the bulk of the soil, a steady withdrawal of moisture by these roots will reduce water percolation so that leaching of fertilizer P from these manures will be retarded.

5.3.2.3 *Methods to improve the conditions for fertilizer P uptake*

The position of the fertilizer in the soil with respect to soil depth and distance to plant roots may be of relevance for the conditions for fertilizer P uptake.

When placed below the seed and separated from it by a thin layer of soil to avoid burning damage to germinating seeds, the fertilizer P will be utilized practically from the moment seminal roots start to develop. Whether these roots are able to supply fertilizer P to the plant at a sufficient rate throughout the growing season is, however, doubtful. Due to ageing, they will probably loose their ability to absorb water and nutrients before the plants mature. In an early stage of plant development, they have already been surpassed in number, size and extension by the crown roots. These spread laterally in successive whorls from the crown at a few centimetres above the seeds, and thus well above the fertilizer. Side roots of these roots will penetrate into the soil affected by the P fertilizer, thus continuing the utilization of fertilizer P during the rest of the growing season.

When placed next to a plant hole at a depth where the basal parts of the crown roots will be formed, the fertilizer P will probably be out of reach of downward-developing seminal roots, but within easy reach of crown roots and subsequently developing brace roots. After seedling establishment, the soil affected by the fertilizer will be intensively covered by roots developing from newly-formed whorls, so that fertilizer P might be steadily absorbed.

During dry spells in the growing season most topsoils dry out rapidly, especially in the granite and rhyolite soils, due to high evaporation rates and small amounts of available water. Hence, when placed beside or just below the seed, the fertilizer is located at a level where the soil

Table 1. Composition of cow dung, sewage sludge and 'Rowo'soil at the time of application in terms of dry matter (70 °C).

	Cow dung of four 'boma's'				Sewage sludge	'Rowo' soil
	Field 6	Field 15	Field 12	Field 8		
Moisture (mass %) (a)	75	85	156	178	15	22
Moisture (mass %) (b)	51			58	50	
Organic matter (mass %) (c)	11	12	22	27	46	
pH(H_2O)	6.5	7.6	7.8	7.5	6.0	6.8
P(total) (mg/kg)	1,860	1,953	3,906	3,720	9,703	15,531
P(Olsen) (mg/kg)			605		367	43
P(H_2O) (mg/kg)	57	80	341	308	81	7
N (g/kg)	3.92	5.42	8.95	8.99	26.01	
K (g/kg)	7.00	10.48	16.85	10.36	2.23	
Ca (g/kg)	3.28	4.00	6.72	8.20	14.68	
Mg (g/kg)	1.48	0.80	1.87	3.40	1.34	
Na (g/kg)	0.53	0.92	3.34	0.41	1.40	
NO_3 (g/kg)	5.33	0.99	0.19	1.05	0.62	
SO_4 (g/kg)	0,00	0,00	0.05	0,00	2.21	
Cl (g/kg)	0.21	0.21	0.89	0.50	0.11	
Cd (mg/kg)			0,2		3.1	
Cu (mg/kg)			32		401	
Zn (mg/kg)			159		1,550	
Pb (mg/kg)			42		528	
Fe (g/kg)			83		25	
Mn (g/kg)			3.4		2.1	

(a) moisture content at application
(b) moisture content after air-drying and rewetting at pF-2
(c) estimated from loss-on-ignition

may be frequently dry. Since fertilizer P can be taken up only from a moist soil, such dry spells may affect its rate of recovery. Recovery might increase when P is placed more deeply in the soil, where the soil is moist over a longer period and P uptake is less frequently interrupted.

When triple superphosphate is concentrated in a single location and when, due to the low amounts applied or a high P-sorption capacity, the volume of soil affected by the fertilizer is small, the number of active roots present in this volume may be so limited that, even though they absorb P at a maximum rate, they cannot adequately supply the plants. In such circumstances, P recovery might be increased when more fertilizer is applied in one location or when the fertilizer to be applied is spread over more locations near the plant, so that the volume of the soil affected by the fertilizer is enlarged and more roots can participate in the uptake of fertilizer P.

However, when more triple superphosphate is applied below the seed, the risks of injury to the seminal roots increases as the high concentration and high acidity which develop at the site of granules after application are likely to be maintained for a longer period in a larger volume of soil and residual fertilizer. Furthermore, the concentrated solution, may, due to its specific mass of up to 1.3 kg/l (Lindsay and Stephenson, 1959), move rapidly downwards in a water-saturated soil after rainfall. If, in addition, the P sorption proceeds slowly or the P-sorption capacity is not large enough to retain the passing fertilizer P, a portion might be leached from the topsoil and become out of easy reach of the roots.

If, on the other hand, P displacement is slow and P sorption high, or if the sorption is enlarged by the high P concentration and high acidity of the fertilizer solution, placement of large amounts of triple superphosphate below the seed might not affect a volume of soil large enough to ensure adequate uptake of fertilizer P. When, under such circumstances in the unaffected portion of the soil, the availability of native P is very low, maximum crop yields might not be obtained. Distribution of the triple superphosphate over more locations near the plant may partially eliminate this constraint. Since the labour involved in making holes and applying fertilizer increases linearly with the number of holes, it remains to be seen, however, whether the additional benefits outweigh the additional costs.

For an evaluation of the various placement methods, references with triple superphosphate broadcast and incorporated in the tilled layer were included in the trials. To examine how yield increases resulting from placement of fertilizer P compare with those obtained when the P-fixation capacity of the soil in the whole tilled layer is quenched and optimum concentration of P in the soil solution is reached and maintained, treatments consisting of large doses of broadcast and worked-in triple superphosphate were included in the experiments.

On the basis of the previous reasoning, it was decided to include the following methods of application in the trials:

1 single subseed placement (placement of triple superphosphate in plant holes below the seeds in a single application at the start of the trials;
1.1 subseed placement (placement in immediate contact with soil);
1.2 protected subseed placement (placement without immediate contact with soil);
1.2.1 placement in cow dung;
1.2.2 placement in sewage sludge;
1.2.3 placement in 'Rowo' soil;
2 repeated subseed placement (placement of triple superphosphate in plant holes below

the seed, whereby an equal amount of P was applied at the start of each growing season);

3 placement of triple superphosphate beside plant holes in a single application at the start of the trial;

3.1 scattered placement (placement in either 2 or 4 holes at a depth of about 7 cm below the soil surface);

3.2 deep placement (placement in 2 holes at a depth of about 15 cm below the soil surface);

4 mixing (broadcasting and incorporation of triple superphosphate throughout the tilled layer to a depth of about 16 cm in a single application at the start of the trial).

To examine whether shortages of K, Mg, S, Cu, Zn, B and Mo limited crop production, treatments with applications of these nutrients were included in the trials.

5.3.3 Rates of P application

To be in line with the low-input strategy and to avoid seedling damage in the placement treatments, emphasis was laid on low rates of P application. For the subseed-placement experiments initiated in the first growing season, the rates of P applied were: 11, 22, 33, 44 and 131 kg/ha (in P_2O_5: 25, 50, 75, 100 and 300 kg/ha), which for 55,555 plants per ha corresponded with 0.2, 0.4, 0.6, 0.8 and 2.4 grams of P per plant hole. To examine whether or not high grain yields could be obtained with subseed placement exceeding the usual P rates and whether or not burning damage could become serious, the P rate of 131 kg/ha was included in the trials. For the placement experiments initiated in the second and third season, the rates of P applied were 5.5, 11 and 22 kg/ha (in P_2O_5: 12.5, 25 and 50 kg/ha; in P per hole 0.1, 0.2 and 0.4 grams).

For the experiments in which triple superphosphate was mixed with the soil, the P rates were selected on the basis of results obtained in laboratory experiments in which the P-sorption capacities of the soils were determined (Table 2, Figure 9). As highest P rate, a rate was chosen with which a final P concentration in the soil solution well above that of 0.2 mg/l, 'The Standard P Requirements', could be obtained and which could be expected to guarantee maximum yields during three successive growing reasons. To allow comparison with placement treatments, some P rates used in these treatments were included. To facilitate comparison between the fields, the same rates were used: 33, 66, 131, 262, 524, 1,048 and 2,096 kg/ha (in P_2O_5: 75, 150, 300, 600, 1,200, 2,400 and 4,800 kg/ha), which corresponds with 0.65, 1.3, 2.6, 5.2, 10.4, 20.8 and 41.6 mmol P per kg of soil or 20, 40, 81, 161, 322, 645, 1,290 mg P per kg soil, assuming an incorporation depth of 16 cm and a bulk density of 1 kg/l. For soils with medium or high P-sorption capacities, 2,096 kg P per ha was chosen as the highest rate and 66 kg P per ha as the lowest rate, while for the volcanic-ash soils with a low P-sorption capacity, these values were 1,048 and 33 kg/ha respectively. Thus, for each soil six P levels were chosen.

This relatively large number of levels was considered necessary to cope with the expected phenomenon of P fixation affecting the shape of the successive response curves. If, for instance, no yield responses were to be found at the lower rates in the third season, it would still be possible to draw a reliable residual response curve with the yield data obtained at the higher P rates.

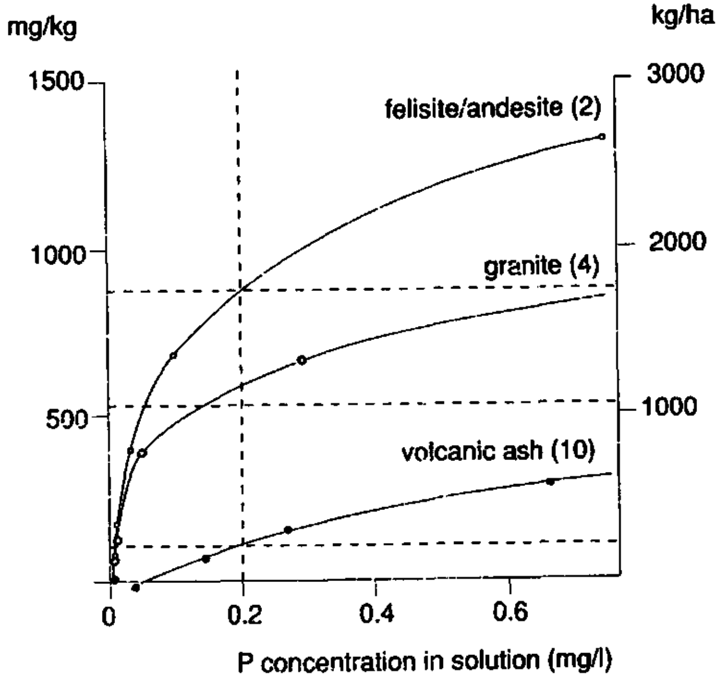


Figure 9. Relationships between P sorption and P concentration in soil solution.

5.4 SELECTION OF TRIAL FIELDS

5.4.1 Criteria

The selection was aimed at obtaining fields where the availability of P was the main factor limiting crop production and P fixation could be expected. Therefore, the fields had to meet the general requirement that soils should have a low availability of native P and should be able to sorb large quantities of fertilizer P. Some fields should have reference soils in which the native P availability was high and/or P-sorption capacity low. Further field requirements were:

- The soils should have been formed in situ and the geology of both soil material and underlying rock should be known. Soils developed on slopes with a gradient steeper than 8 percent or situated directly below ridges or steep slopes, and soils that had developed near geological boundaries were excluded.
- The soils should be (naturally) well-drained. This requirement yields soils with low risks of surface run-off, ponding and waterlogging.

Table 2. Characteristics of the seventeen soils selected on five parent materials.

	Granite				Rhyolite			Basalt			Felsite-andesite			Volcanic ash			
	4 [a]	6 [b]	14	15 [b]	9	12 [b]	13 [a]	3 [a]	5	8 [b]	1	2 [b]	7 [a]	10 [a]	11 [b]	16	17
Topsoils (0 - 20 cm)																	
P(total) (mg/kg)	539	549	634	490	593	675	622	620	1017	920	879	1035	1391	2081	1681	770	4796
P(Olsen) (mg/kg)	1.8	1.6	2.0	1.6	3.9	3.0	3.4	2.0	2.2	2.4	3.4	3.2	5.2	37.6	59.6	2.8	16.7
P sorption [c] (mg/kg)	560	660	500	580	285	445	330	710	580	810	810	870	560	105	60	320	50
$pH(H_20)$	5.2	4.7	5.5	4.9	6.0	5.2	5.8	5.8	5.6	5.2	5.3	5.5	5.8	6.0	6.2	5.8	7.7
pH(KCl-1 mol/l)	4.2	4.0	4.5	4.1	5.0	4.5	4.9	4.7	4.7	4.3	4.4	4.4	4.9	5.1	5.2	4.8	6.8
C(org.) (mass%)	2.0	2.3	2.7	2.0	2.3	2.6	2.0	2.4	4.2	3.5	4.2	4.8	4.7	7.7	3.0	4.0	2.5
N (mass %)	.14	.17	.19	.13	.16	.19	.12	.21	.36	.34	.38	.40	.44	.61	.26	.36	.18
CEC [d] ($mmol_c$/kg)	118	130	144	116	183	160	134	182	270	233	242	262	259	374	230	232	491
Ca^{2+}(exch.)($mmol_c$/kg)	37	23	61	32	115	67	94	111	144	88	88	97	192	275	172	144	690
Mg^{2+}(exch.) ($mmol_c$/kg)	13	11	18	12	35	29	25	27	32	25	29	27	37	44	31	23	83
K^+(exch.) ($mmol_c$/kg)	8	4	10	4	15	9	10	11	20	12	18	22	20	23	20	7	58
Clay (%)	28	38	32	30	34	31	24	28	34	33	22	22	24	11	16	13	23
Silt (%)	31	32	36	27	35	50	51	59	59	61	67	68	68	78	74	78	66
Sand (%)	41	40	32	43	31	19	26	13	7	6	11	9	9	11	10	9	11
Water retention (pF-1.0) (%)	60	67	65	58	60	64	57	65	84	79	88	86	85	104	77	83	79
Water retention (pF-2.0) (%)	28	31	30	28	29	34	36	42	44	41	45	44	45	68	55	58	55
Water retention (pF-4.2) (%)	14	17	18	15	14	20	16	18	24	23	21	23	24	28	21	24	28

	Granite				Rhyolite			Basalt			Felsite-andesite			Volcanic ash			
	4 [a]	6 [b]	14	15 [b]	9	12 [b]	13 [a]	3 [a]	5	8 [b]	1	2 [b]	7 [a]	10 [a]	11 [b]	16	17
Subsoils (50 - 70 cm)																	
P(total) (mg/kg)	396	369	362	378	388	480	395	391	673	601	650	712	749	953	1055	338	5047
P(Olsen) (mg/kg)	1.3	0.9	1.4	1.4	1.4	0.9	1.8	0.0	1.9	1.9	0.9	0.9	1.4	9.3	34.4	1.8	4.2
pH(H_2O)	5.1	5.3	4.9	5.0	6.2	5.6	5.9	6.1	6.0	5.6	5.3	5.9	6.3	5.8	6.6	6.3	7.9
pH(KCl-1 mol/l)	4.2	4.2	4.1	4.1	4.8	4.4	4.6	4.7	4.6	4.4	4.4	4.8	5.0	4.8	5.2	5.0	6.9
C(org.) (mass%)	1.1	1.2	1.1	1.0	1.4	1.6	1.2	0.9	1.6	2.3	2.0	1.9	2.7	2.6	1.0	1.3	0.9
CEC [d] ($mmol_c$/kg)	95	91	91	81	161	121	147	149	161	201	174	187	230	210	160	127	345
Ca^{2+}(exch.)($mmol_c$/kg)	29	16	17	16	101	48	86	87	67	88	50	91	158	135	125	81	562
Mg^{2+}(exch.) ($mmol_c$/kg)	9	6	7	4	34	23	24	26	21	23	28	32	33	19	26	22	84
K^+(exch.) ($mmol_c$/kg)	2	2	1	1	5	3	4	3	7	3	5	8	7	7	10	4	31

(a) indicates fields that were selected for the basic trials
(b) indicates fields that were selected for the basic and further trials in the second and third growing season
(c) P sorption at a P concentration of 0.2 mg/l
(d) determined with ammonium acetate (1 mol in equilibrium solution, pH-7)

Table 3. Characteristics of the trial fields and sampling sites.

Field	Location	Sublocation Market	Farmer's name	Position	Slope (%)	Altitude (m)	Parent material	Soil type Subgroup (a)
1	West Mugirango	Nyachogochogo	Ogao Onsinyo	top-slope	1-3	1890	felsite-andesite	typic Paleudoll
2	East Kitutu	Magombo	Stanley Obaga	top	0-2	1900	felsite-andesite	typic Paleudoll
3	South Mugirango	Bogetenga	Silas Ondiege	top-slope	2	1600	basalt	typic Paleudoll
4	Kamagambo	Koderopara	Anyanyo Ochola	top-slope	3	1500	granite	orthoxic Palehumult
5	Majoge Chache	Bochi	Maraba School	slope	5	1640	basalt	typic Paleudoll
6	South Mugirango	Nyandigwa	Osano Obutu	top	0-3	1550	granite	orthoxic Palehumult
7	South Mugirango	Boikanga	Serenusi Matiabe	top	0-2	1850	felsite-andesite	typic Paleudoll
8	Majoge Chache	Bochi	Samuel Onyancha	slope	1-5	1720	basalt	typic Paleudoll
9	Gem	Kanyaluth	Raphel Ochola	slope	3	1380	rhyolite	oxic Argiudoll
10	Borabu	Mwongori	Mary Morara	top	0-3	2150	volcanic ash	pachic andeptic Hapludoll
11	Borabu	Nyansiongo	Charles Matara	top	0-2	1860	volcanic ash	pachic andeptic Hapludoll
12	Sakwa	Ranen	Gabriel Oyara	slope	4-6	1430	rhyolite	typic Paleudoll
13	Sakwa	Ranen	Pius Othiambo	slope	3-4	1420	rhyolite	oxic Argiudoll
14	Wanjare	Bomariba	Mbabu Onsarigo	top	0-2	1570	granite	orthoxic Palehumult
15	Wanjare	Bogitaa	Obutu Nyamwange	top-slope	2-4	1550	granite	Tropudult
16	Nyaribari Masaba	Nyamasibi	Doris Sonye	top	0-2	2170	volcanic ash	pachic andeptic Hapludoll
17	Mbita	Kirindo	Min. of Agriculture	slope	2-4	1150	volcanic ash	fluventic Haplustoll

(a) according to Soil Taxonomy (Soil Survey staff, 1975)

- The solum should have a depth of more than 1 m. This requirement allowed the selection of soils with a low drought hazard and with little influence of the underlying rock on both root distribution and nutrient supply.
- The fields should measure at least 30 m by 60 m, a minimum size for the basic trials. In densely-populated areas, many fields were too small.
- The fields should be in cultivation for annual food crops and the current crops should be fairly uniform in appearance. These requirements were set to avoid unwanted variations in soil fertility within fields. In densely-populated and intensively cultivated areas, several annual and perennial crops were usually found growing in one field, either in monoculture in small plots or in various combinations in a mixed cropping system, and for that reason such fields had to be excluded. In extensively cultivated areas, remnants of previous bush vegetation, such as solitary trees, were often found, and so these fields were also excluded.
- The field should have a fairly smooth surface. This requirement excluded fields affected by hill-building termites. With the construction and subsequent erosion of termite hills, soil material is selected, transported and sorted (Wielemaker, 1984). The consequence of this kind of biological activity is probably the formation of radial soil fertility gradients perpendicular to termite hills.

5.4.2 Procedure

The fields were selected with the use of detailed soil maps (1 : 12,500) compiled by the staff and graduate students of the Training Project in Pedology (Wielemaker & Boxem, 1982) and of geologic maps of the Kisii area (Huddleston, 1951).

Trials were planned on traditional farms located on the major soil types. Preliminary fields were selected in 1976, when the general requirement could not be applied definitely as the necessary laboratory work and pot trials had not yet been completed. Therefore, the preliminary selection was based on the nature of the parent materials from which the solum had developed. The major parent materials in the area are basalt, an association of felsite and andesite, granite, rhyolite and volcanic ash (Figure 3).

Since the major parent materials occur in different regions and often also at different altitudes, fields differing in parent material will probably also vary with respect to other factors, for instance climate. To reduce the danger of confounding effects of various factors, an attempt was made to select the fields at comparable altitude or at a short distance from each other. Two fields were selected in the major area of each parent material, while a third one was selected in a minor area, if such a minor area occurred at a short distance from major areas of other parent materials.

The locations of the tentatively selected fields are shown in Figure 1 and 2. The soils from these fields were sampled and analysed extensively for several soil characteristics (Table 2 and 3).
Most soils were low in available P (P-Olsen) and had a high P-sorption capacity, according to the P-sorption scale proposed by Juo & Fox (1977). Soils high in available P and low in P-sorption capacity were also present: pure volcanic ash soils in small areas on the eastern

borders of the survey area (Fields 10 and 11) or distant from the survey area, near Lake Victoria (Field 17). These volcanic ash soils are also characterized by a high content of P (P-total), a high cation-exchange capacity (CEC), high contents of exchangeable potassium, magnesium and calcium, and good physical properties. Fields 10 and 11 were obviously better than Field 17 in properties such as pH and P-Olsen.

Maize plants developed P-deficiency symptoms (purple colouring) and showed a reduced growth rate when no P fertilizer was applied in pot experiments using the double-pot technique as described by Janssen (1974). P limited plant growth especially on the granite, rhyolite, basalt and felsite-andesite soils, indicating the low native P availability of these soils.

For a final selection, the fields were arranged in order of increasing compliance with the requirements set. Fields 17, 9, 16, 1, and 5 were excluded for the following reasons: Field 17 because of the availability of more suitable reference soils; Field 9 because of uncertainties about the origin of the parent material; Field 16 because of variation in thickness and colour of the A horizon. Field 1 because of lower uniformity than the equivalent Field 2; and Field 5 because of lower accessibility than the equivalent Field 8. The final selection consisted of eleven fields (Table 2, Note a). After the first growing season, Fields 2, 6, 8, 11, 12 and 15 were chosen for additional trials in the second and third growing season (Table 2, Note b). On Fields 3, 4, 7, 10 and 13 the trials were stopped after the second season.

5.5 TIME SCHEDULE OF THE FIELD RESEARCH PROGRAMME

The field research programme is presented schematically in Figure 10. Experiments involving subseed placement and mixing were initiated in the first growing season on all experimental sites. They were continued in the second season and on a selected number of sites, also in the third season, to determine the residual effects of placed and mixed fertilizer on crop yield and to calculate the P recovery over three successive growing seasons. In the subseed-placement experiments at P rates of 11 and 33 kg/ha, the application of the initial amount was repeated at the start of the second and third season (repeated-subseed placement) in order to study the combined initial and residual effect of the fertilizer.

In the second growing season the following placement experiments were initiated on a number of sites: 1. subseed placement; 2. protected subseed placement in sewage sludge, in cow dung or in 'Rowo' soil; 3. scattered placement, and 4. deep placement. Grain yield, P uptake and distribution over the plant tissue during the growing season and P recovery were determined. These experiments were continued in the third season for the determination of the residual effects of the differentially placed fertilizer on grain yield and P recovery. On a few control plots, and on some plots of the subseed-placement experiments that received P (22 kg/ha) in the second season, 22 kilograms of P was applied below the seed at the start of the third season, so that initial, residual and combined initial and residual effects could be compared in the same growing season.

In the third season, on the main experimental sites, detailed studies were made on the behaviour of fertilizer P in the soil and on the effect of placed triple superphosphate on early plant development, particularly on root development. The behaviour of fertilizer P in the soil was studied both in the absence of plants in separate experiments started in the third season, and in the presence of plants in experiments initiated in the first, second or third season. The changes in composition of triple superphosphate granules were studied in experiments in which granules were mixed with soil or placed in soil either singly or in cow dung and sewage sludge. At the same time, movement and sorption of fertilizer P that had dissipated from the granules into the soil were studied in relation to the quantity of P applied and of the method of application.

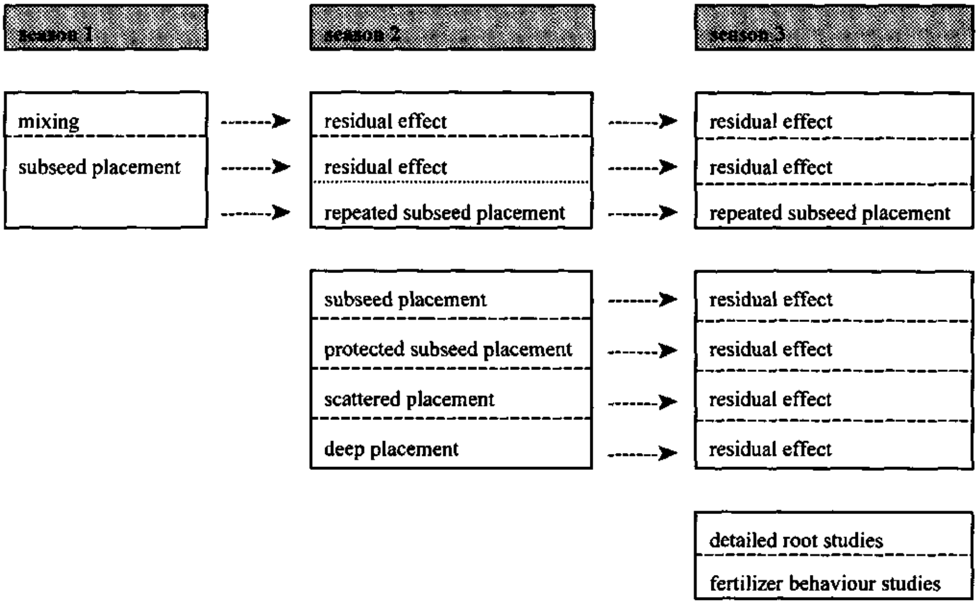


Figure 10. Time schedule of the research programme.

5.6 LAYOUT OF THE TRIALS

The trials that were initiated in the first season consisted of 18 experimental units. The units were arranged according to a randomized block design in 3 replicates (Appendix 1). They were: subseed placement P: 11*, 22*, 33*, 44, 131 kg/ha; mixing P: 66, 131, 262, 524, 1,048, 2,096 kg/ha; control* (no P); control with applications of K, Mg, S, Cu, Zn, B and Mo; P: 524 kg/ha (mixed) with applications of K, Mg, S, Cu, Zn, B and Mo. The rates were: K 50, Mg 20, S 58, Zn 15, Cu 8, B 1.5 and Mo 2 kg/ha. In the third season, all treatments of Fields 6, 15 and 12 received a maintenance application of K, Mg and S. The rates were: K 40 and Mg 20 and S 43 kg/ha for a second crop and K 50 and Mg 25 and S 53 kg/ha for a third crop. Units indicated with * were present in duplicate per block.

The plot size was 18 m^2 (3 m by 6 m) and the plots contained 100 plants in 5 rows each with 20 plants (Appendix 1). The net plot contained 48 plants, 3 rows each with 16 plants, and this number of net plants was reduced to 45 and 42 in the second and third season respectively. It decreased by 1 plant per row each season, due to the way the fields were replanted (Figure 11). Around every trial field, at least two additional rows were sown to avoid side-effects.

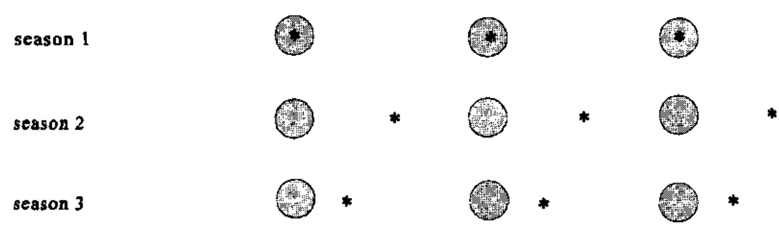


*Figure 11. The position of maize plants (*) and remaining placed fertilizer (shaded areas) in a row during three subsequent growing seasons. Plant distance: 0.3 * 0.6 m.*

For the placement experiments that were initiated in the second season, a randomized block design was used with 4 replicates. The number of experimental units varied among the fields from 7 to 30 per block (Appendix 2 A and B). The units were selected from the following treatments: control; subseed placement P: 5.5, 11, 22 kg/ha; protected subseed placement in cow dung, in sewage sludge, or in 'Rowo' soil P: 0, 11, 22 kg/ha; scattered placement in two holes or in four holes P: 22 kg/ha; deep placement P: 22 kg/ha. Cow dung, sewage sludge and Rowo soil were applied at a rate of 100 cm^3 per plant. Of the treatments: control; subseed placement P: 22 kg/ha; protected subseed placement P: 0 and 22 kg/ha extra units were included for intermediate harvests during the growing season. In most trials, the control treatment and the subseed placement treatments P: 11 and 22 kg/ha occurred in two units per block.
The plot size was 8.64 m^2 (2.4 by 3.6 m). The number of net plants was 30, either in 3 rows of 10 plants (Appendix 2 A) or in 5 rows of 6 plants (Appendix 2 B). As only placement treatments were involved, it was assumed that a relatively small number of border plants would be sufficient for avoiding side effects from neighbouring plots. These border plants growing at the boundaries of the plots acted like a buffer between net plants on either side. To support their growth, they received a small amount of triple superphosphate in the plant hole (P: about 2 kg/ha). Due to the way the fields were replanted, the number of net plants per plot was reduced in the third season to 27 (3 rows of 9 plants) or 25 (5 rows of 5 plants).

In the placement experiments of the third season, the experimental units were systematically arranged in 4 blocks. The layout of 1 block is shown in Appendix 3. The number of units per block varied among the fields from 4 to 10. Each unit consisted of a row with 7 plants, of which the central 5 were considered to be the net plants. The units were selected from the following treatments: control; subseed placement P: 22, 44, 131 kg/ha; protected subseed placement in cow dung or in sewage sludge P: 0 and 22 kg/ha; scattered placement in two holes P: 22 kg/ha; and deep placement P: 22 kg/ha. References with placement of fertilizer in the absence of plants were also included.

6 EXECUTION OF THE RESEARCH

6.1 PREPARATION OF THE FIELDS

Fields were cleared of all vegetation by slashing. The cut-down vegetation was raked together and removed from the fields. The land was then tilled with either a disc plow or a mouldboard plow. A few weeks later, seedbeds were prepared with a rotary tiller. Most fields needed a second cultivation to obtain the desired 20 cm thickness of the tilled layer and a uniformly finely-structured soil. The stubble and tough couch-grass roots, Digitaria Scalarum, present at the soil surface were raked together and removed from the fields.
In the second and third growing season, seedbeds for the additional trials were prepared by hand with a forked hoe ('fork jembe'). The stubble and major part of the couch-grass roots, to a depth of about 20 cm, were uprooted and removed from the fields.

6.2 PROPERTIES OF THE MATERIALS

6.2.1 Fertilizers

Commercial triple superphosphate was used as the only chemical P fertilizer in the trials. Table 4 lists the chemical composition. The fertilizer contained a mass fraction of P of 20 % (46 % P_2O_5) and consisted of spherical granules with a diameter of about 3 mm.

Calcium ammonium nitrate with a mass fraction of N of 26 % was used as a nitrogen fertilizer. In some treatments, K_2SO_4, $MgSO_4.7H_2O$, $CuSO_4.5H_20$, $ZnSO_4.7H_2O$, H_3BO_3 and $(NH_4)_6Mo_7O_{24}.4H_2O$ were used to supply the major nutrients K, Mg and S and the trace-nutrients Cu, Zn, B and Mo.

Table 4. Composition of triple superphosphate (mass %)

$Ca(H_2PO_4)_2.H_2O$	67.5
$Ca(HPO_4).2H_2O$	5.0
$Ca_3(PO_4)_2$	3.0
H_3PO_4	7.5
H_2O	3.0
$CaSO_4.nH_2O$	2.0
CaF_2	3.0
$(Fe,Al)_x(SO_4,PO_4)_y$	4.0
(Al,Mg)-silicates	3.0
SiO_2 and Ca-silicofluoride	2.0

Source: Windmill Laboratories, Vlaardingen, The Netherlands.

6.2.2 Protective materials

'Boma' cow dung, sewage sludge and 'Rowo' soil were used in trials of the second and third growing season. Table 1 shows some data on the composition of these materials.

The cow dung was collected in the neighbourhood of the trial fields from paddocks ('bomas') in the open near the farmers' houses, where cattle stayed overnight. Farmers keep their cattle for several years in one boma. Then, the cattle are transferred and the dung remains for some time before it is collected and used as manure. Well-decomposed dung was scarce. Therefore, less decomposed and, hence, less-structured 'boma' cow dung was used in the trials.
The composition of the 'boma' dung varied from field to

field. Such variation was to be expected, as the composition of fresh dung was found to differ from area to area and its age varied from boma to boma. Weather, influencing decomposition and nutrient losses from dung, may add to the variability in composition. Soils also affected the composition, as cows had trodden the dung and mixed it with the soil, and soil-borne animals further mixed and homogenized the material, lowering the organic matter content of the dung.

The sewage sludge was obtained from the sewage works in the town of Kisumu. It was derived from household sewage. This dry, black, well-structured friable material had high contents of N and P. The contents of heavy metals, such as Cd (3 mg/kg), Cu (401 mg/kg), Pb (528 mg/kg) and Zn (1,550 mg/kg) were similar to those of urban household sewage sludge in the Netherlands.

The 'Rowo' soil was collected from the crater centre of the extinct Rangwe Volcano near Lake Victoria. The soil had a high P content. In comparison with most trial field soils, the content was about twenty times as high.

6.3 METHODS OF APPLICATION

6.3.1 Fertilizers

Triple superphosphate was either mixed with topsoil or placed in or near plant holes. If mixed, the fertilizer was broadcast by hand as uniformly as possible and then incorporated uniformly to a depth of about 16 cm in one cultivation with a rotary tiller. Figure 12 shows the position of the fertilizer after mixing. For placement, holes were made with a sharp-edged open fruit-juice tin with a diameter of 6.5 cm. Occasionally, sharpened bamboo sticks were used instead of tins in the first growing season. When the tin was pushed into moist well-tilled soil and withdrawn carefully, a column of soil remained in the tin and a flat-bottomed cylindrical hole appeared in the soil. With these tins, holes could be made exactly at the desired spot, shape could be standardized and depth controlled. Triple superphosphate was applied with a number of plastic spoons, each calibrated for a particular rate of application. The fertilizer granules were distributed over the bottom of the plant hole and then the hole was filled with soil. If the fertilizer was placed in the same holes as used for sowing, the fertilizer was covered with about 2 cm of soil. The seed was then placed and the hole was filled with soil. Figure 12 shows placement of fertilizer in the plant holes. Triple superphosphate was usually placed at a depth of about 7 cm. If deeper, holes were made with an 'Edelman' auger.

Calcium ammonium nitrate was applied at equal rates in all trials. In the first and second growing season, the fertilizer was applied 6 weeks after planting. Around each plant, a shallow circular furrow with a radius of about 12 cm was drawn with short sticks. The fertilizer was measured out and distributed over the furrow with a calibrated spoon and then covered with soil. In the third growing season, the fertilizer was applied twice, viz. at planting and 9 weeks after planting. At planting, it was broadcast and incorporated in the soil with a 'jembe'. At 9 weeks, it was top-dressed and harrowed in with a 'fork jembe'. In the first and second growing season, rates of N were 60 kg/ha. In the third season, 80 kg/ha was used in a combination of 40 kg/ha at planting time and 40 kg/ha at 9 weeks after planting. On Fields 6, 12 and 15, an extra N application was made in the third season 12 weeks after planting, at a rate of 30 kg/ha.

The fertilizers for K and Mg, alone or in combination with Zn, Cu, B and Mo, were placed in the same plant holes made for placement of triple superphosphate. In the third season, the maintenance application of K, Mg and S was broadcast and incorporated in the soil with a 'jembe' at planting time.

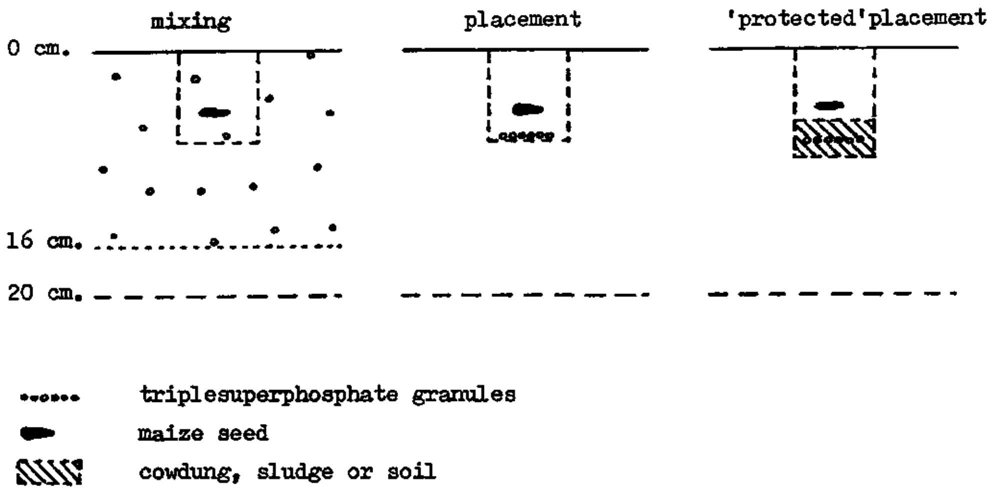


Figure 12. Positions of triple superphosphate fertilizer granules, protective materials and maize seeds in the soil.

6.3.2 Protective materials

'Boma' cow dung, sewage sludge and 'Rowo' soil were placed in plant holes. The holes were made about 9 cm deep with a tin, as described for placement of triple superphosphate. If the materials were placed in combination with triple superphosphate, 50 cm^3 of either cow dung, sewage sludge or 'Rowo' soil were applied below and 50 cm^3 above the triple superphosphate. A thin layer of soil was added to separate the seeds from the applied materials (Figure 12).

6.4 METHODS OF PLANTING

In the first growing season, maize was sown in cylindrical holes, made with a tin as described in 6.3.1. In the second and third growing season, this method was practised only when fertilizer was placed inside the plant holes. When fertilizer was placed beside the plant holes, or when the trials were replanted in order to study the residual effect of the fertilizer, maize was sown in conical holes made with a 'panga'.

Seeds were placed at a depth of about 5 cm (Figure 12) in rows with 30 cm distance between plants and 60 cm between rows, with a total of 55,555 plants per hectare. Two seeds were placed in each hole to increase the chance of obtaining a complete and uniform plot of maize seedlings. Three weeks after planting, the seedlings were thinned. When both seedlings were missing, new seeds were placed.

In all trials, the hybrid maize variety no. 512 was used. The seeds were supplied by the Kenyan Seed Company in Kitale.

6.5 MANAGEMENT OF THE TRIALS

Fields were weeded 3, 6 and 9 weeks after planting. Later in the season, the leaf canopy of the crop intercepted most of the sunlight and thus hindered further weed growth. Weeding was preferred rather than using herbicides, as weeding loosened the surface soil, so that surface run-off was minimized with heavy rains. Witchweed was found to grow on two trial fields and parasitized on the roots of maize plants. To limit damage to the crop and to prevent witchweed from multiplying by seeds, these fields were weeded more often. To accelerate weed dying, to minimize damage to maize roots and to avoid dispersion of placed fertilizer, weeding was done shallowly with a 'jembe'.

Cutworms and stalk borers lived in most fields in low numbers and were successfully combatted with 'Furadan 10 G' insecticide, when applied in the plant holes at a rate of about 10 kg/ha at planting and in the whorl of the plant at a rate of 5 kg/ha 6 weeks after planting. Whorl application had no side-effects on maize growth, not even at a rate of 5 times the usual quantity. Brown spot, leaf blight and diplodia were rarely observed. The damage to the crop was insignificant and no control measures were taken.

Fields were fenced against cattle, sheep and goats. Proper use was made of thorn hedges planted by the farmers to fence their fields. Where necessary, new fences were made from barbed wire. Groundvoles living in a few fields locally destroyed young maize plants. Voles were combatted with a rodenticide. Birds of various species ate maize kernels from the time they were soft and milky. The maize ears in the trial fields were not damaged or only slightly damaged when the maize in the farmers' fields grew simultaneously. If not, damage was considerable, in spite of the various measures that had been taken to scare off the birds. Porcupines and other rodent species that lived in small numbers near the fields locally ate mature and nearly-mature maize ears. Termites lived on all trial fields in large numbers. Only lodged mature plants were eaten by them. To limit grain losses, maize was harvested as early as possible after having reached maturity.

Gusts of wind and hail storms damaged plants in some of the trials each season. Yield losses were small when the plants were damaged early in the season, at a stage in their growth that they could still straighten themselves and form new leaves. However, yield losses were serious when plants were damaged shortly after stalk elongation and plants could no longer recover. At that stage, recently lodged plants were sometimes placed upright and, if no heavy storms followed, plants continued growing without noticeable set-backs.

Shortly after the harvest, the trial fields were prepared for a following crop. Weeds were slashed and removed from the fields. The fields were then tilled with a 'jembe' to a depth of about 10 cm. Both operations were carefully performed in such a way that most of the previous maize crop stubble and, hence, also the fertilizer placed below the seed remained in position. The skilful Gusii and Luo labourers were thus able to minimize the transport of soil and fertilizer residues and thus created favourable conditions for studying the residual effect of the fertilizer and for replanting. The maize stubble marked the position of the placed fertilizer, so that the plants of the following crop could be easily sown in the previous rows between the remaining maize stubble (Figure 11).

6.6 OBSERVATIONS AND SAMPLING

6.6.1 Observations

At every visit to the trials, the crop's appearance was assessed and attention was paid to nutrient-deficiency symptoms and pests.

For all experimental units, plant heights were measured nine weeks after planting in each season. At that time, stalk elongation was in progress and large differences in plant heights were recorded between the units. Twelve plants were systematically selected, so that each row and each part of a plot contributed equally to the determination of the mean plant height. If a selected plant was absent, seriously damaged or sown three weeks later, neighbouring plants were taken instead. They were straightened along a calibrated stick and the highest leaf tip was taken as the plant height. If the plants within a plot varied considerably in height, more than twelve plants per plot were measured.

Particularly in the third growing season, plant growth was observed carefully. At three, six and nine weeks after planting, several plant properties were measured, such as plant height, number of leaves, maximum width of the biggest leaf, diameter of the stalk at the base, height of the growing point, dry matter production of green plant material, number of permanent roots, number of root whorls in the crown, diameter of the roots near the whorls and distribution of plant roots in the soil.

6.6.2 Accessory data gathering and investigations

Meteorological data were collected during the trials. They were partly gathered from weather stations in the Kisii area and partly measured in the trial fields during the second and third growing season.

Special studies were carried out by graduate students of the Wageningen Agricultural University on a few selected fields. The effects of solar radiation, vegetation, mulch, soil surface colour and soil moisture content on the daily thermal fluctuations in soil were studied in the first season by Oenema (1978). He also studied the effect of combined application of organic manure and triple superphosphate fertilizer (Oenema 1980, I and II) The effects of rainfall, maize vegetation, weeds and mulch on soil moisture content were studied in the third season by de Koning (1982) and Slofstra (1984).

6.6.3 Plant sampling

In the first and third growing season, a selected number of experimental units were sampled nine weeks after planting. From each of five or six systematically selected plants per plot, the youngest full-grown leaf was removed. The leaves were washed in rainwater and cut into pieces. Then, they were air-dried and oven-dried at 70 °C and sent to the Department of Soil Science and Plant Nutrition in Wageningen for chemical analysis.

In the second season, some experimental units were harvested six and twelve weeks after planting. Twelve plants per plot were cut a few centimetres above the soil surface. Six-week old plants were washed in rainwater and air-dried with their whorl cut open longitudinally. They were then cut into pieces and oven-dried at 70 °C. The dry weight was determined and a 10 to 20-gram sample was taken for chemical analysis. All plant parts contributed proportionally to the sample. Twelve-week old plants were subdivided into stalks and leaves. The fresh weights were measured and samples were taken for moisture determinations and chemical analysis. To obtain representative samples, parts of the stalks and leaves were cut out at regular distances. Samples were taken at 20 to 30 cm, 70 to 80 cm, 120 to 130 cm, et cetera, from the stalk base and at 10 to 15 cm, 30 to 35 cm, 50 to 55 cm, et cetera, from the leaf base. The samples were air-dried and oven-dried at 70 °C and then 10 to 20-gram sub-samples were taken, in which all parts contributed proportionally.

Grain samples for moisture determination and chemical analysis were taken each season. In the first season they were taken from most of the treatments and in the second and third season from all treatments. The samples were taken at random after shelling in quantities of 100 to 150 gram.

Mature plants of a few experimental units were harvested in the first growing season. Six plants per plot were systematically chosen and subdivided into grains, ear axes, husks, stalks, upper leaves and lower leaves. The ear axes, husks, stalks and leaves were cut into short pieces. The fresh weights were determined and samples were taken at random for moisture determination and chemical analyses. As cutting stalks and leaves into short pieces was very time-consuming, and as random sampling was difficult to carry out representatively, another method of sampling was used in the second season.

Mature plants from several experimental units were harvested in the second growing season. Nine or ten plants per plot were systematically chosen and subdivided into grains, ear axes, husks, stalks and leaves. Fresh weights were measured and samples were taken for moisture determination and chemical analyses. Ear axes and husks were first broken and cut into short pieces, before 100 to 150-gram ear axis samples and 50 to 100-gram husk samples were taken at random. Stalk and leaf samples were taken as described for sampling of twelve-week old plants. However, the sample sizes were adjusted to the sizes of the plants by varying the length of the plant parts that were cut out of the stalks and leaves. If sample sizes were still too large, some plant parts were removed randomly from the sample in order to obtain 125 to

200-gram stalk samples and leaf samples of not more than about 60 grams. The samples were air-dried and oven-dried at 70 °C. The dry weights were determined and about 50-gram grain subsamples and 10 to 20-gram sub-samples of ear axis, husk, stalk and leaf were each taken at random (grain and husk) or pieces of all plant parts were snipped of, so that each part contributed proportionally to the sub-sample (ear axis, stalk and leaf).

6.6.4 Soil sampling

The methods and schemes of soil sampling depended on the way P fertilizers had been applied.

Mixing: Top-soil samples were taken with an Edelman auger from the 3-12 cm depth layer, at 45, 67 and 88 weeks after application. Per net plot, ten samples were combined to form a composite sample. Sampled treatments were P: 0, 66, 131, 524, 2,096 or 1,048 kg/ha. Each replicate of the treatment was separately sampled. At week 88, sampling was confined to the six soils on which trials were continued in the third season (Fields 2, 6, 8, 11, 12 and 15). Sub-soil samples were taken from freshly cut walls of pits measuring 200 * 100 * 70 cm, which were dug in the centre of a net plot after the final harvest at week 88 following the start of the trials. They were taken at depths of 25-30 and 55-60 cm. Sampling was restricted to one replicate and to the treatments P: 0, 131, 2,096 or 1,048 kg/ha at the six soils where trials were continued in the third season. Soil horizons were sampled from pit walls.

Placement: Soil below the fertilizer residue was sampled in the following way. A trench was dug along a row to a depth of about 40 cm. The soil above the fertilizer residue was carefully removed with a spade. After the fertilizer residue had been sampled (Chapter 6.6.5) and removed altogether, cylindrical segments of soil with a diameter of 5 cm and a height of 2 cm were cut out with a knife and collected with a spoon at depths of 0-2, 2-4, 4-6 and 18-23 cm below the fertilizer. Per treatment, five segments were used to form a composite sample. The treatments were P: 0, 22, 44 and 131 kg/ha; protected subseed placement in cow dung and in sewage sludge at a P rate of 22 kg/ha. Samples were taken 3, 6, 9 and 24 weeks after application in the absence of plants, and 55 and 85 weeks after application in the presence of plants. Sampling was restricted to five soils where trials were continued in the third season (Field 2, 6, 8, 11 and 12).

The fresh soil samples were air-dried under cover of a tent sheet or in a ventilated storehouse. To accelerate drying, large top-soil and sub-soil samples were laid out on paper sheets. If large soil aggregates occurred, they were crumbled during the drying to facilitate sieving. The dried samples were sealed in plastic and transported to the Department of Soil Science and Plant Nutrition in Wageningen for analysis.

6.6.5 Sampling of P fertilizer and protective materials

Triple superphosphate, sewage sludge, cow dung and 'Rowo' soil were sampled at the time of application. Samples of sewage sludge, cow dung and soil were first air-dried, by leaving the plastic bags in which they were sampled open and then oven-dried at 50 °C. The dry samples were sealed in plastic and transported to the Department of Soil Science and Plant Nutrition in Wageningen for analysis.

Residues of placed fertilizer, and fertilizer placed protectively in sewage sludge or in cow dung, were collected with a small spoon and a pair of tweezers, after the covering soil layer had been carefully removed (Chapter 6.6.4). The sampled treatments were the same as for soil sampling with placement. Single residual granules from original broadcast application that could be still observed at the end of the trials were collected with a small spoon in plots where P was applied at a rate of 2,096 kg/ha. The fertilizer residues were air-dried immediately at the sampling site and put into plastic tubes. Just before transportation to the Netherlands, they were oven-dried at 50 °C to avoid moisture condensation inside the tubes at low temperatures during transport.

6.7 PLANT, SOIL AND FERTILIZER ANALYSES

Plant material was digested with sulphuric-salicylic acid. P, N, K, and in some samples Mg, Ca, Na, NO_3, Cl and SO_4 were determined as described by Slangen & Hoogendijk (1971).

Soil samples were sieved with a 2 mm sieve.

Total P and available P:
For total P, soil material, fraction < 2 mm, was digested with Fleischmann's acid and P concentration was measured with molybdate-blue colouring measured at 720 nm (Houba et al. (1976). Available P was measured with sodium bicarbonate (Olsen et al., 1954). Olsen's method was chosen as it is one of the methods widely used for tropical soils. It is assumed to extract part of the Al-and Fe-phosphate, part of the Ca-phosphate and part of the organic-P (Beck & Sanchez, 1994) In some of the soil samples, available P was also measured with de-ionised water (Pw; Sissingh, 1971) or with acid-fluoride (Bray & Kurtz no 1, 1945).

P sorption and desorption in the laboratory:
Soil material, fraction < 2 mm, was ground briefly to obtain a fraction < 0.2 mm. A sample of 0.5 gram was moistened for 2 days with 0.5 ml de-ionised water. Then 40 ml KCl (0.01 molair) was added, to which P was applied in the form of KH_2PO_4 in P concentrations of : 0, 1, 2, 4, 8, 16, 32 mg/l. The pH of the KCl-KH_2PO_4 solutions were all adjusted with KOH to the pH of the soil in a solution of KCl (0.01 molair; soil/solution = 0.5/40). During the sorption period, the pH was not regulated. After the sorption period, pH was measured in the solution with an original P concentration of 8 mg/l. Sorption time was 5 days and temperature 20 °C. During the sorption period, the tubes were gently shaken end-over-end with vertical rotation. After the sorption period, tubes were centrifugated at 20,000 rpm for 20 minutes. The solutions were decanted and P concentrations were measured with molybdate-blue colouring at 720 nm in a 1 cm cuvet, or at low P concentration at 880 nm in a 4 cm cuvet. The P-sorption capacity was assessed by plotting the calculated amount of P sorbed versus the measured final P concentration as shown in Figure 9 and reading the sorbed amount at a final P concentration of 0.2 mg/l (6.5 μmol/l). The sorption measurement was directly followed by a desorption measurement. In three subsequential desorption steps, P was desorbed by adding 40 ml

KCl (0.01 molair). Desorption time was 22 hours. The circumstances were similar to those for P sorption.

P sorption and desorption in the field:
In samples taken from soil layers directly below placed fertilizer (rates of 22, 44 and 131 kg/ha) and from the tilled layer in which fertilizer was mixed (rates of 512 and 2,096 kg/ha), total P was measured. The amount sorbed was calculated as the difference in total P between fertilized and non-fertilized soil. Available P was measured with sodium bicarbonate (P-Olsen) or de-ionised water (Pw).

Compositional changes in soil enriched with fertilizer and fertilizer residues were monitored with optical microscopy, X-ray diffraction, scanning electron microscopy and X-ray micro-analysis (Henstra et al. 1981; Boekestein et al. 1981).

Several other soil properties were measured using standard procedures in the laboratories of the Department of Soil Science and Plant Nutrition and the Department of Soil Science and Geology, such as organic C (Kurmies); native soil P sources, viz: Ca-phosphates, Al + Fe - phosphates, and organic phosphates (Kurmies); total Nitrogen; K, Ca, Mg, Mn, Fe, Al, Si, Ti, P (with rontgenfluorescence); K, Na, Ca, Mg, Mn, Fe, Al, Si, Ti (with HF destruction); CEC, plus exchangeable Ca, Mg, K (ammonium acetate, 1 N, pH-7); pH-H_2O (1:2.5); pH-KCl (1 molair, 1:2.5 or 0.01 molair, 1: 60); particle size (organic matter was destroyed with hydrogen peroxide, carbonates and iron coatings were removed with HCl and clay fraction was dispersed with sodium pyrophosphate); water retention characteristic.

6.8 METHODS OF HARVESTING AND YIELD CALCULATIONS

6.8.1 Harvesting

Husks were opened with a knife and ears were removed. Ear quality was assessed and then the ears were shelled at the field site. All the consumable grains of a net plot were weighed and then sampled as described in Chapter 6.6.3 In other words, all grains affected by pests were excluded. After the ears had been harvested, the plants were slashed about 5 cm above the soil surface and carried from the field.

6.8.2 Assessment of yield

In order to obtain more detailed experimental results, data on the following plant parameters were collected at harvest:
- The number of plants destroyed before flowering.
- The number of plants damaged after flowering in such a way that ears with kernels could not be formed (coded as Pl).
- The number of plants with zero, one or two ears.
- The number of ears without kernels 'barren'(Eb).
- The number of ears with more than 85 % of the kernels destroyed (Ed).
- The number of ears with part of the kernels destroyed (Edp). An ear had part of the kernels

destroyed when the estimated consumable mass fraction was less than 0.85 of the original kernel mass.
- The number of ears with consumable kernels (Ec). Ears with more than 85 percent of the kernel sites occupied were qualified as good ears (Ecg) and ears with less than 85 percent as poor ears (Ecp).

6.8.3 Yield quantification and correction for damaged plants

Grain yields were expressed in kg per ha on the basis of a mass fraction of moisture of 12 %. If plant, ear or kernel losses had occurred, the yields were corrected in order to get a more realistic picture of the experimental results. The corrections were made with the following assumptions:
- Loss of plants before flowering was not involved in the correction, since it was assumed that neighbouring plants would compensate fully for the grain losses, provided the number of lost plants was small. Only when groundvoles had been active could the number of plants lost be so high that the gaps were too large to justify an assumption of full compensation. On these rare occasions, yield was corrected either by reducing the net plot size or by estimating grain yields from plant height nine weeks after planting.
- Plants that had not formed ears or had developed ears that were barren or had a poor kernel setting were assumed to be an experimental result and, hence, were not involved in the correction.
- Plants that were damaged after flowering (Pl) would, under normal conditions, have formed ears with kernels. For the correction, it was assumed that neighbouring plants were not able to compensate for the grain losses, since the damage occurred after flowering when plants were already full-grown. It was further assumed that the damaged plants would have formed ears with a grain yield equal to that of the other consumable ears of the same plot denoted as Ec ears. Plants denoted as Pl plants had either been eaten by animals or had been so severely damaged by wind that they could not form ears or the ears of the lodged plants were destroyed by animals or fungi.
- Plants that had formed ears with kernels being completely or partly destroyed before harvest were denoted as Ed or Edp ears. For the correction, it was assumed that these ears would have given a grain yield equal to that of the other ears of the same unit that were denoted as Ec ears. Ears denoted as Ed or Edp ears had either been eaten by animals or affected by fungi.
- Plants that had formed ears with an uneven and poor kernel setting as a result of wind damage were not involved in the correction. Although yield losses were often obvious, a reliable correction for assessing these losses could not be made, because either all plants were lodged and had consequently formed unevenly-set ears or the few plants that were not lodged had formed larger than normal ears. In such situations, undamaged plants with normally developed ears were not available for comparison.

For experimental units in which a fraction of the plants had formed two ears with kernels the following assumptions were added:
- The formation of two ears per plant was assumed to be an experimental result. Plant density, soil fertility and climate are apparently the most important factors regulating the

number of ears per plant. A fraction of the plants on the Fields 10, 11, 2 and 7 formed two ears. It occurred most frequently on Field 10, where up to 25 % of the plants formed two ears, while on Fields 11, 2 and 7 less than 5 % of the plants usually formed two ears. However, when two ears had developed on lodged plants or on plants near gaps, the formation of two ears was assumed to be a result of lodging or of a reduced plant density. In such situations, plants with two ears were counted as though they were plants with one ear.
- When maize plants form two ears, the top ear (first ear) is large and the bottom ear (second ear) small. Since the relative differences in size appeared to be fairly constant among the units of a field in a season, it was assumed that the grain yield of a second ear was a constant mass fraction of the grain yield of a first ear.
- Plants that were damaged after flowering (Pl) or had formed ears that were completely destroyed (Ed) were assumed to have had equal chances of forming two ears in comparison with other plants of the same plot.
- When plants of which the first ear was completely destroyed (Ed_1) had formed a second ear, this second ear was assumed to have been completely destroyed as well.
- Plants of which the second ear was completely destroyed (Ed_2) were assumed to have formed a first ear that was denoted as either an Ec_1 or Edp_1 ear.

For plots in which plants were qualified as Pl plants and ears as Ed or Edp ears, the weighted yields were multiplied with a correction factor (F). The factor is a ratio. Its denominator is the sum of the number of ears with consumable kernels and the number of ears with part of the kernels destroyed multiplied by the estimated mean consumable mass fraction of the original kernel mass. Its numerator is the sum of the number of ears with consumable kernels, the number of ears with part of the kernels destroyed, the number of ears with all kernels destroyed and the number of plants damaged after flowering. Hence, the sum of the numerator is equal to the potential number of ears. The correction factor usually had a numerical value lower than 1.3. For units that consisted of plants with not more than one ear per plant, the correction factor (F_a) is defined as follows.

$$F_a = (Ec + Edp + Ed + Pl)/(Ec + aEdp)$$

where Ec, Edp, Ed and Pl have meanings as defined in Chapter 6.8.2 and a is the estimated mean consumable mass fraction of the original kernel mass. For units consisting of plants with two ears, the correction factor was composed of two terms. The first term transformed second ears and partly destroyed ears into equivalent ears and the second term corrected for completely destroyed ears and plants. The resulting correction factor (F_b) is defined as follows.

$$F_b = \{(Ec_1+bEc_2) + (Edp_1+bEdp_2) + bEd_2\}/\{(Ec_1+bEc_2) + (a_1Edp_1+a_2bEdp_2)\} * (Ec_1 + Edp_1 + Ed_1 + Pl)/(Ec_1 + Edp_1)$$

where Ec, Edp, Ed and Pl have meanings as defined in Chapter 6.8.2, a as defined before, and b stands for estimated mean mass fraction of the grain yields of second ears in relation to the grain yields of first ears. The suffices 1 and 2 indicate first and second ear respectively.

To clarify the procedure of the yield correction two examples are given, one for the use of F_a and the second for the use of F_b.

<u>Example 1:</u> Fresh weight of the net plot yield equals 4,000 grams. Fresh weight of the grain sample equals 150 grams. Dry weight of the grain sample equals 115 grams. Net plot size equals 8.10 m^2. Plant qualifications are: Total number of plants in the net plot 45, of which 1 plant was destroyed before flowering and 2 plants were damaged after flowering (Pl). Ear qualifications are: Total number of first ears 42, of which 3 ears were barren (Eb = 3), 30 ears had kernels all suitable for human consumption (Ec = 30), 5 ears had part of the kernels destroyed (Epd = 5) and 4 ears were completely destroyed (Ed = 4). The estimated mean consumable mass fraction of the original kernel mass of partly destroyed ears is 0.6 (a = 0.6).

Calculation of yields:
- without corrections for losses:

Y = 4,000 * 115/150 * 100/88 * 10,000/8.10 * 1/1,000 = 4,302 kg/ha

- with corrections for losses:

F_a = (Ec + Edp + Ed + Pl)/(Ec + aEdp) = (30+5+4+2)/(30+0.6*5) = 41/33 = 1.24

Y corrected = F_a * Y = 1.24 * 4,302 = 5,345 kg/ha

Notes:
1 The value of the numerator of the correction factor is 41 and not 45, the latter being the number of plants in the net plot. This is in accordance with the assumptions that the grain yield loss of plants destroyed before flowering is fully compensated and that the formation of barren ears is an experimental result.
2 Grain yield per ear is 0.106 kg and the potential number of ears per hectare is 50,617.

<u>Example 2</u>: Idem Example 1, but in addition second ears were harvested with the following qualifications:

Total number of second ears 7, of which 4 ears had kernels all suitable for human consumption (Ec_2 = 4), 2 ears had part of the kernels destroyed (Edp_2 = 2), and 1 ear was completely destroyed (Ed_2 = 1). The estimated mean mass fraction of grain yields of second ears in relation to grain yields of first ears is 0.7 (b = 0.7).

Calculations of yields:
- without correction for losses: Y = 4,302 kg/ha

- with correction for losses:

F_b = {(Ec_1+bEc_2) + (Edp_1+bEdp_2) + bEd_2}/{(Ec_1+bEc_2) + (a_1Edp_1+a_2bEdp_2)} * (Ec_1 + Edp_1 + Ed_1 + Pl)/(Ec_1 + Edp_1)

F_b = {(30+0.7*4) + (5+ 0.7*2) + 0.7*1}/{(30+0.7*4) + (0.6*5+0.6*0.7*20} * (30 + 5 + 4 +2)/(30 + 0.6*5) = 39.9/36.64 * 41/35 = 1.28

Y corrected = F_b * Y = 1.28 * 4,302 = 5,488 kg/ha

Note:

Grain yields per first and second ear are 0.095 and 0.067 kg respectively, while the potential number of first and second ears per hectare are 50,617 and 10,123 respectively.

7 RESULTS

In this chapter the results of the field trials are presented. The results of the preliminary laboratory measurements and the greenhouse experiments were mainly used for selecting the trial fields. Relevant data on these results are given in Table 2 and Figure 9.

7.1 YIELD RESPONSE TO FERTILIZER P APPLICATION

7.1.1 Incorporation of broadcast fertilizer P (mixing)

Application of fertilizer P clearly increased yields on the soils on granite, rhyolite, basalt and felsite/andesite (Figure 13; for yield data see Appendix 4). This finding makes it evident that native P was the limiting factor for grain production even on soils with relatively high grain yields. In general, low yields due to P shortage can result from low levels of available P resulting from low levels of total P or from low levels of available P in spite of high total-P levels. Since the soils in the present experiments, except for the reference soils, have low P-Olsen values and normal P-total values (Table 2), the yield limitation can be ascribed to a low availability of native P. The yield responses were obtained every season and at each application rate, which indicates that fertilizer P remained available during three successive growing seasons, even when applied at the lowest rate of 66 kg/ha.

On the volcanic-ash soils (Fields 10 and 11), maize did not respond to fertilizer P application. As control yields, P-Olsen values and total-P values were high, and P-sorption capacities were low for these soils, the lack of response should be ascribed to a high availability of native P and not to fixation of fertilizer P.

On the other soils, a large yield increase was already obtained at the lowest P application rate (66 kg/ha). For the soils on which three crops were grown, the average yield increase per crop at this rate varied from 1,566 to 2,850 kg/ha. The response curves levelled off at rates above 262 and 524 kg/ha. This finding suggests that up to these rates the availability of fertilizer P determined the grain yields and that above these rates factors other than P were yield-limiting.

7.1.2 Placement of fertilizer P

7.1.2.1 *Subseed placement*

Grain yields clearly increased on the soils on granite, rhyolite, basalt and felsite/andesite, but not on the volcanic ash soils (Figure 14; for yield data see Appendix 4). The responses were obtained every season and at each application rate (except in a few cases), which indicates that placed fertilizer P remained available for plants during three successive growing seasons. On the other hand, the response curves did not level off on most of the soils and the yields obtained at the highest P rate of 131 kg/ha were below the maxima found with mixing, which shows that the availability of fertilizer P was still yield-limiting at this rate.

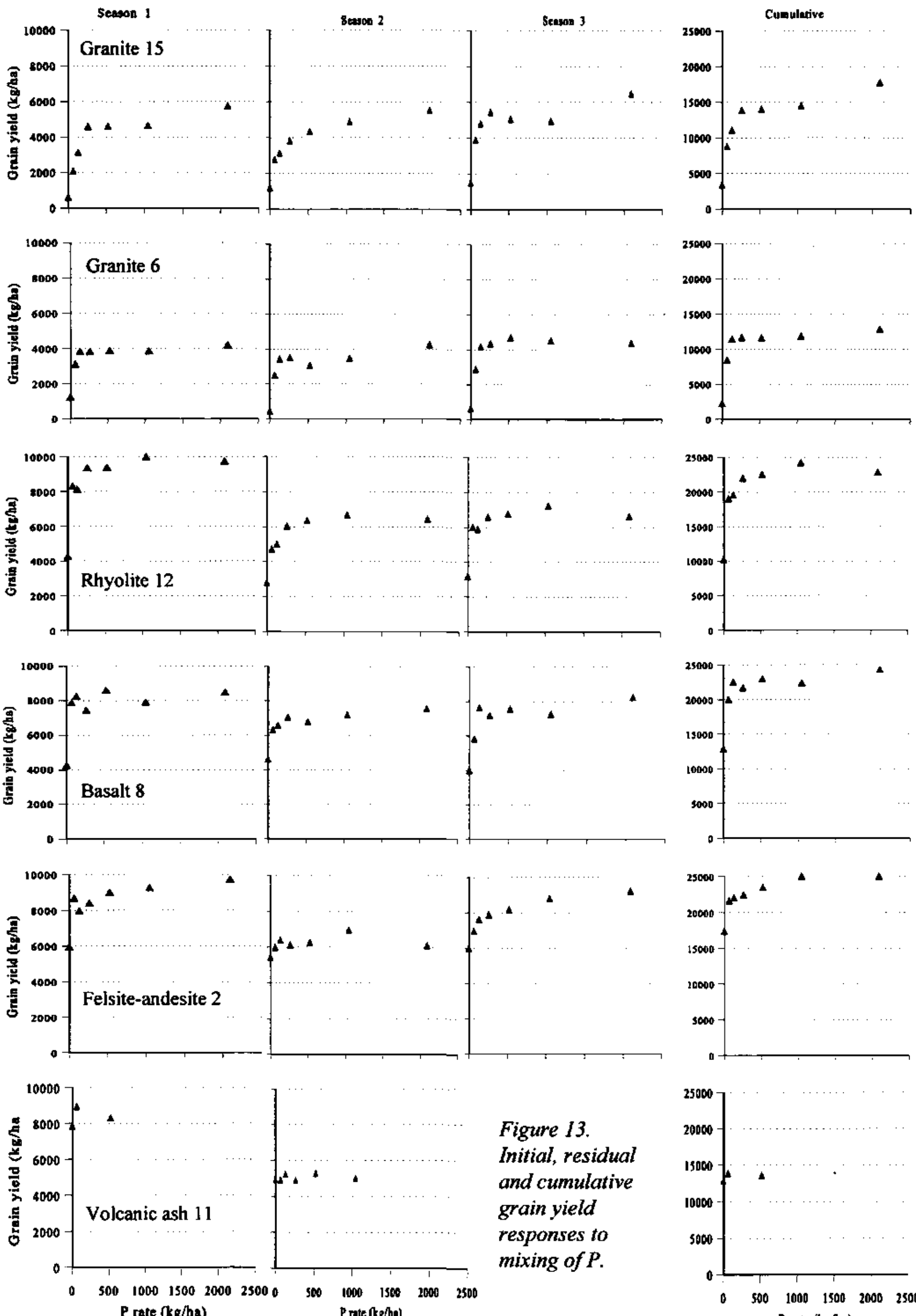


Figure 13. Initial, residual and cumulative grain yield responses to mixing of P.

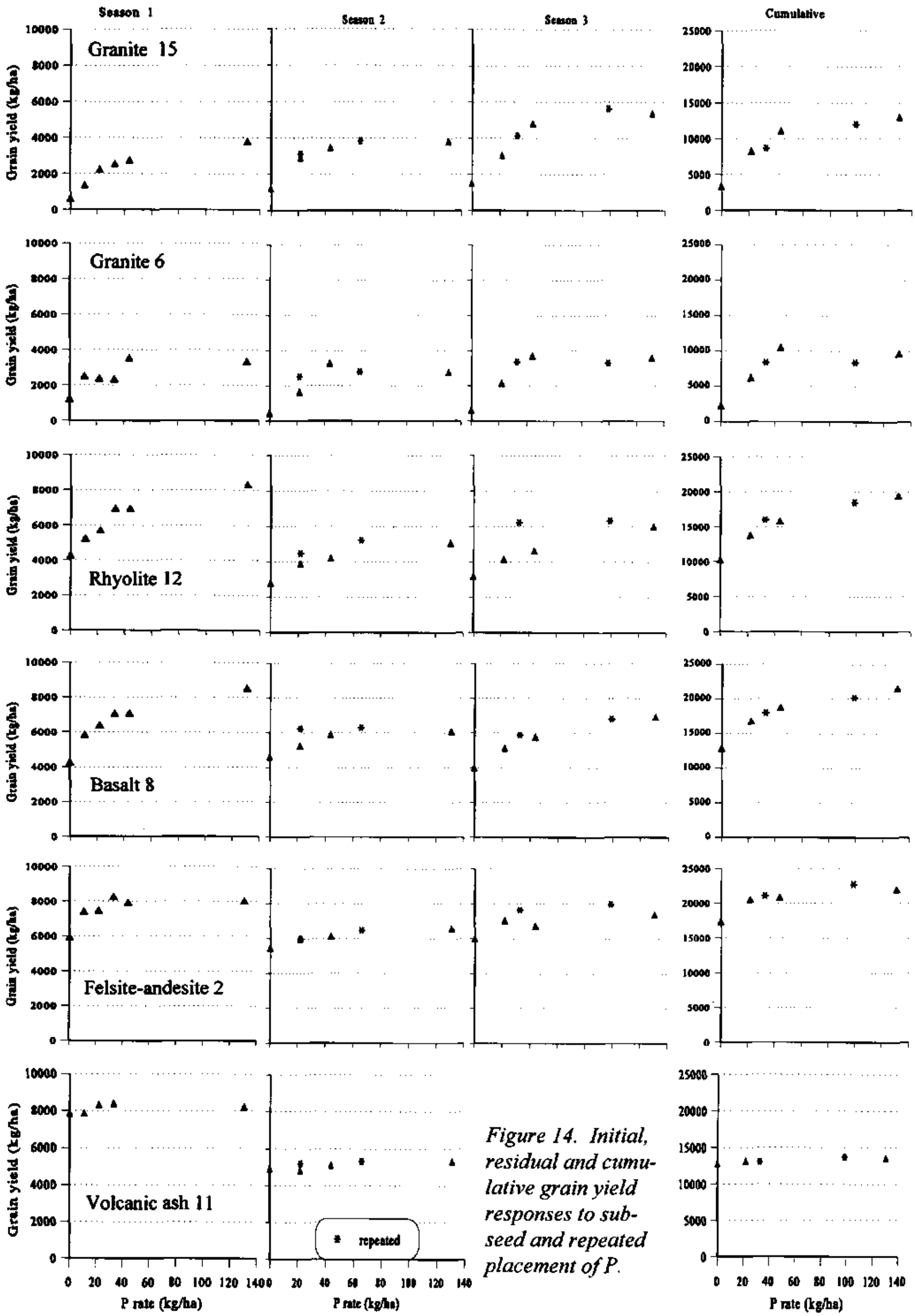


Figure 14. Initial, residual and cumulative grain yield responses to sub-seed and repeated placement of P.

7.1.2.2 *Subseed placement versus mixing of fertilizer P*

To facilitate comparison of the cumulative results of three growing seasons obtained with mixing and subseed placement, P rates were plotted on a logarithmic scale in Figure 15. In every season and on all soils, the data for both methods of application were almost in line, which indicates, that at equal application rates, subseed placement and mixing resulted in about equal grain yield. Only the granite soil (Field 15) seems to form an exception. For this soil, subseed placement resulted in higher yields in the range of overlapping P-application rates. However, the differences in position and slope of the calculated regression lines for subseed placement and mixing were not significant ($P = 0.10$). The same holds when the individual seasons are considered, with the exception of the difference in position of the lines in the third season. Then, subseed placement resulted in a significantly ($P = 0.05$) higher grain yield than with mixing.

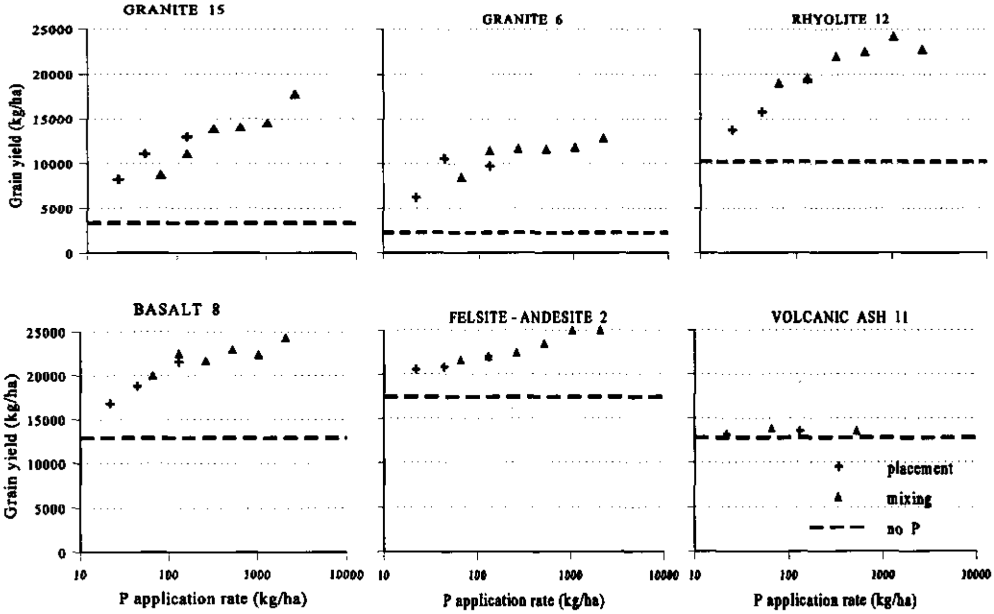


Figure 15. Comparison of the effects of subseed placement and mixing of fertilizer P on grain yield cumulated over three growing seasons.

7.1.2.3 *Repeated subseed placement*

Two of the five P rates in the first season, namely 11 and 33 kg/ha, were repeated in the second and third season. In Figure 14, the grain yield responses obtained with both methods are compared in the second and third season and cumulatively over three growing seasons.

Repeated subseed placement gave slightly higher yields than single subseed placement in a particular season but the cumulative yield data for single and repeated subseed placement matched one response curve on every soil fairly well.

7.1.2.4 *Scattered and deep placement*

Scattered and deep placement gave clear initial and residual grain yield responses (Figure 16; yield data see Appendix 5a). There were hardly any differences in yield between subseed placement and scattered placement in two or four holes per plant. Deep placement usually gave lower yields than the other placement methods, especially in the first season. These results indicate that increasing the number or depth of the fertilized sites by splitting the fertilizer doses at the rate used (22 kg/ha) does not result in an increase of the availability of fertilizer P in comparison with subseed placement.

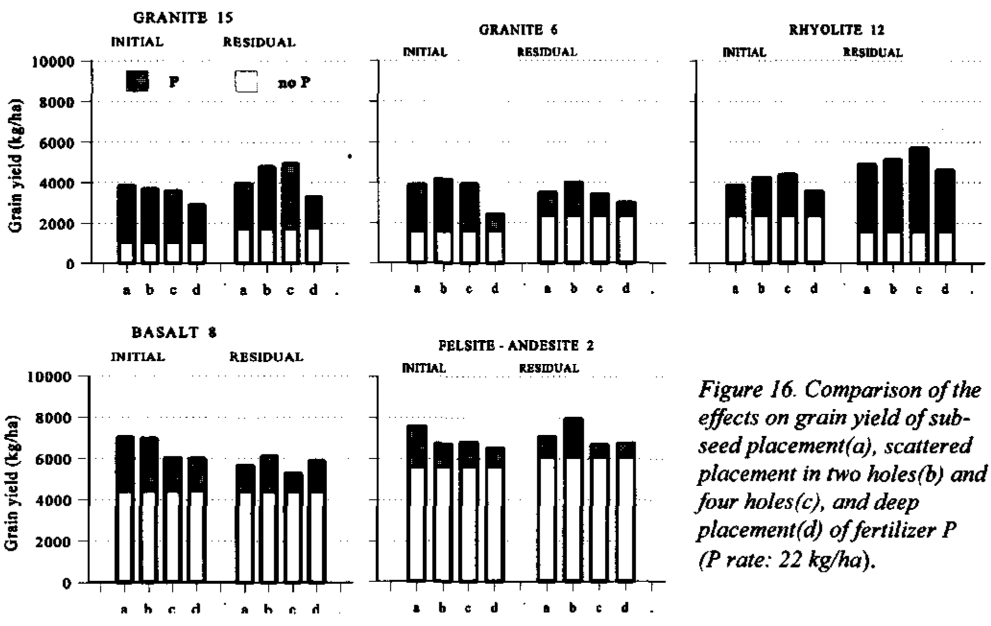


Figure 16. Comparison of the effects on grain yield of subseed placement(a), scattered placement in two holes(b) and four holes(c), and deep placement(d) of fertilizer P (P rate: 22 kg/ha).

7.1.2.5 *Protected subseed placement*

Grain yields obtained with protected and unprotected subseed placement are compared in Figure 17; yield data see Appendix 5b).

The lines for protected placement in cow dung and sewage sludge have slopes rather similar to those for unprotected subseed placement, but are located at a higher level. From this, it can be derived that the effects of cow dung and sewage sludge were mainly additional to the effect of fertilizer P application and that cow dung and sewage sludge did not promote the availability of fertilizer P for plants. Since the lines did not level off, it also means that P seemed to be

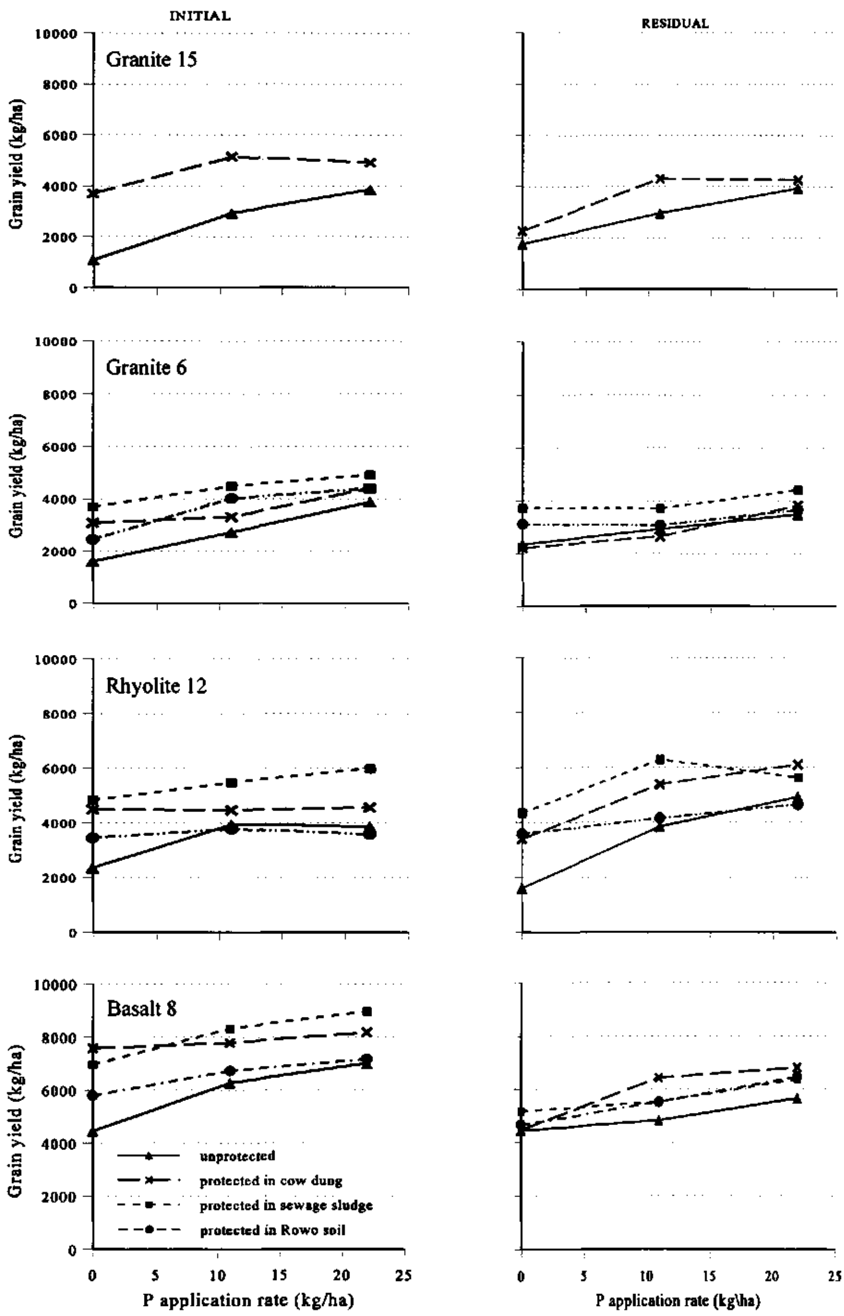


Figure 17. Effects of protected subseed placement on grain yield in two successive growing seasons.

the main limiting growth factor for protected subseed placement.
The residual effects of cow dung and sewage sludge were less than the initial effects, except for the rhyolite soil (Field 12), where they were about equal.
Protection of fertilizer P in Rowo soil resulted in slightly higher or about equal grain yields than without protection, which indicates that Rowo soil did not promote the availability of fertilizer P and that its P supply was of only minor importance.

7.1.3 Other factors influencing yields

Combined application of K, Mg, S, Zn, Cu, B and Mo did not raise yields, neither on the control plots nor on the high yielding P-fertilized (512 kg/ha) plots (Appendix 4). This indicates that none of these nutrients were yield-limiting.
Possible factors limiting or reducing yields were temporary droughts and lodging and, additionally, in the second season low soil temperature and simultaneous N-stress at an early stage of plant-growth, which coincided with the peak of the long rainy season. Since the effects of these factors manifested themselves in various degrees, the yield maxima varied among seasons and fields.
Detailed information for each season is given below and is summarized in Table 5.

Table 5. Factors influencing yield maxima in the trial fields. Numbers refer to fields .

	Season 1	Season 2	Season 3
Nitrogen-stress		all fields	6,12,15
Drought	all fields	4,6,12,13,15	6,8,12,15
Lodging	2,3,7,10,11	2,3,7,8,11	8,12
Hail	7,12	4,6,10	
Low soil temperature		2,7,10,11	
Striga (witchweed)	4,15	4	

First season:
In the first season, water deficiency and, on some fields, lodging or witchweed infestation were yield-limiting factors. The witchweed was probably Striga hermonthica (Smaling, 1993; Press & Graves, 1995).

Because of a drought that lasted four to six weeks, early growth was retarded in all fields and eventually
stopped in a few. Fortunately, once the rains continued, plants recovered and developed normally, except on Field 13, where the drought was most severe and a number of plants did not form ears. Consequently, the response for this field was less marked than for others (Appendix 4). Although the plants on the other fields recovered, the prolonged water stress had probably also suppressed yields on Fields 6, 15 and 8. On some fields, water stress was aggravated by weed growth, which in turn was stimulated by fertilizer P when it was broad-

cast and mixed into the soil. The higher the amount of P mixed into the soil, the more weeds germinated and the faster they grew and thus the stronger they competed with the maize plants for moisture. This side-effect of broadcasting and mixing was most clear on Field 8 in the first season (Photograph 1). Although the fields were weeded every three weeks until tasselling, weeds still suppressed the crop response to P application on some of the fields (particularly on Field 8) in the first season and to a lesser extent in the second and third season.
Despite the severe drought and severe hail damage three weeks after planting, the highest yield obtained in this study was produced in this season on Field 12, which was situated on one of the soils on rhyolite. The highest yield was 10,293 kg/ha. It is uncertain whether higher yields could have been obtained if no drought and hail damage had occurred on this field.

Due to gusts of wind, maize plants lodged during stalk elongation on Fields 3 and 7. At this growth stage, the tall plants of the P-fertilized plots were blown down more easily and erected themselves more slowly than the short plants of the control plots. Hence, wind damage reduced the grain yields of fertilized plants more than those of non-fertilized plants. Although crop responses measured in terms of plant height were obvious at the time the plants lodged, the eventual grain yield responses were small, especially on Field 3, and much smaller than expected on the basis of results obtained on Field 12 (Figure 18). During kernel-filling a large number of plants lodged on Fields 11, 10 and 2, which probably led to a reduction in grain yields on all plots.

Witchweed severely infested Field 4. This parasite reduces grain yields and, since it was unequally distributed over the field, it caused large variability in plant height and grain yield especially in the first season.

Second season:
In the second season, yields were lower than in the first season. Probably the main factors influencing yield were low temperature and N deficiency at an early stage of plant growth. The maize was sown once the long rainy season had already started. Because of the low soil temperature, maize germinated and grew slowly, especially on high-altitude fields (Fields 10, 11, 7 and 2). The average plant height nine weeks after planting on Field 10 was 113 cm, whereas in the first season, with favourable temperatures, it was 171 cm. In the Kenyan Highlands, it has often been observed that maize sown during the rainy season yields less than maize sown at the very beginning of the rainy season. Cooper and Law (1977) ascribed this effect to a lower soil temperature during the rainy season.

N-deficiency symptoms were observed on all fields during vegetative development. They appeared in two forms and at two times.
On the high-altitude fields, seedlings became pale yellowish green shortly after germination. This was most striking on Field 10. It was further observed on all plots of Fields 11, while on Fields 7, 2 and 8 it was most clear on plots where weed growth was abundant due to mixing of fertilizer P at high rates into the soil. Since the N-deficiency symptoms on the high-altitude fields were most pronounced on the soil with the highest organic-N content, the N deficiency might have been caused by a low mineralization rate due to low soil temperature. In addition, part of the mineralized N might have been leached from the topsoil due to excessive rainfall,

while some might have been absorbed by weeds, especially Galinsoga parviflora and Oxalis. These herbs, whose seeds and bulblets were abundantly present on the fertile volcanic-ash soils, grew so rapidly under moist conditions that they were able to cover the entire soil surface within three weeks, which was the time interval between the weedings. Although they were also present on some of the other soils, especially on Field 7, 2 and 8, they only grew rapidly on the heavily P fertilized plots (Photograph 1).
On the lower-altitude fields, pale yellowish plants were not found shortly after germination. Here a V-shaped yellowing of the oldest leaves was observed six weeks after planting. Soon after N was applied, at 6 weeks after planting, the yellowing disappeared, which indicated that N stress had occurred.

Despite the very slow initial development of the plants on Field 10, plants recovered remarkably after the peak of the rainy season and after N application, and finally grew very tall. Unfortunately, a severe hailstorm at flowering seriously shredded all leaves, which reduced grain yields on all plots. Hailstorms also reduced yields on Fields 6 and 4. Yet, on Field 4, the response curve of the second season lay above the curve for the first season because extra weeding in the first season had decimated the witchweed.

Other yield-reducing factors were lodging on Field 11 and, to a lesser and decreasing extent, on Fields 7, 2, 8 and 3, and drought during kernel-filling, especially on Fields 13 and 12.

Third season:
In the third season, probably the main yield-reducing factors were lodging and drought. Lodging strongly reduced yields on Field 12 (Figure 18) and to a lesser extent on Field 8.

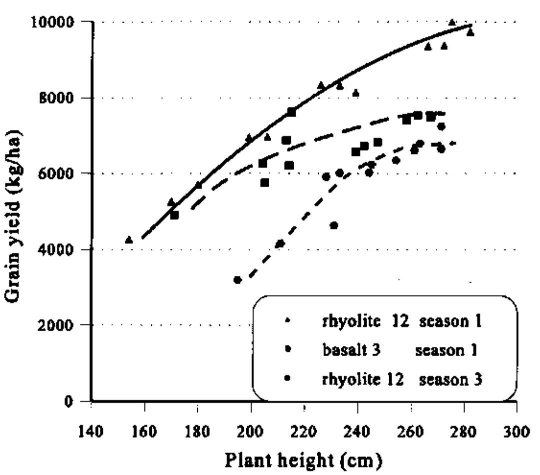


Figure 18. Relationships between plant height at 9 weeks after planting and grain yield: normal growth (rhyolite 12, season 1), with lodging and damage particularly in heavily fertilized plots (basalt 3, season 1); with lodging and damage in all plots (rhyolite 12, season 3).

On Field 12, plant height at nine weeks after planting was about equal to that in the first season, but yield maxima were about 7,000; versus 10,000 kg/ha during the first season. It was mainly drought that limited the yield maxima on Fields 6 and 15.

Photograph 1. Mixing of fertilizer P in the tilled layer stimulated weed germination and growth. In front: to the right, P was mixed at a rate of 2096 kg/ha; to the left, no P was applied. In the middle: P was placed below the seed (Basalt soil, Field 8).

Photograph 2. Fertilizer P stimulated plant development and shortened the growing season. In front of assistent James Nyambane, no P was applied; to the right of him, P was mixed at a rate of 2096 kg/ha. Photograph was taken nine weeks after planting on the granite soil (Field 15).

Since, in this season, N was applied at planting time and soil temperatures were favourable on the high-altitude fields, N-deficiency symptoms did not develop at an early growth stage on any field. On the low-altitude Fields 6, 15 and 12, V-shaped yellowing started in the oldest leaves about seven weeks after planting and it was generally visible nine weeks after planting, the time of the second N application. About a week after the second N application, the colour of the plants turned to a dark green, so that the effect of this temporary N shortage on grain yields was probably relatively small. However, this change in colour was retarded on Field 12 because of drought.

The V-shaped yellowing in the oldest leaves was found to be related to the N content in the youngest full-grown leaf of nine week-old plants (Figure 19). It was weakly, moderately and strongly developed below N concentrations of about 1,900 mmol/kg (27 g/kg), 1,600 mmol/kg (23 g/kg) and 1,300 mmol/kg (18 g/kg) respectively. Leaf N concentrations were related to P application rate and soil type (Figure 19).

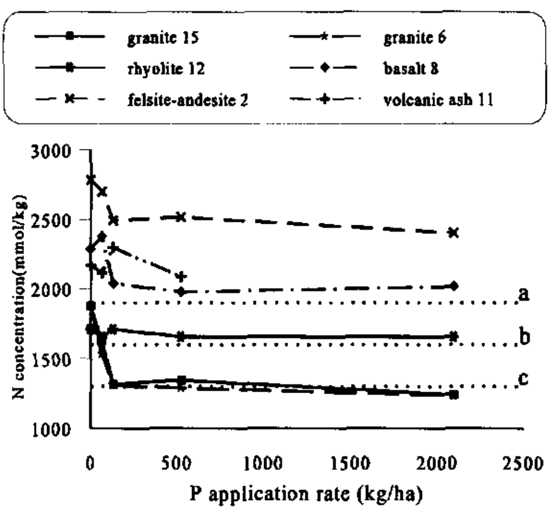
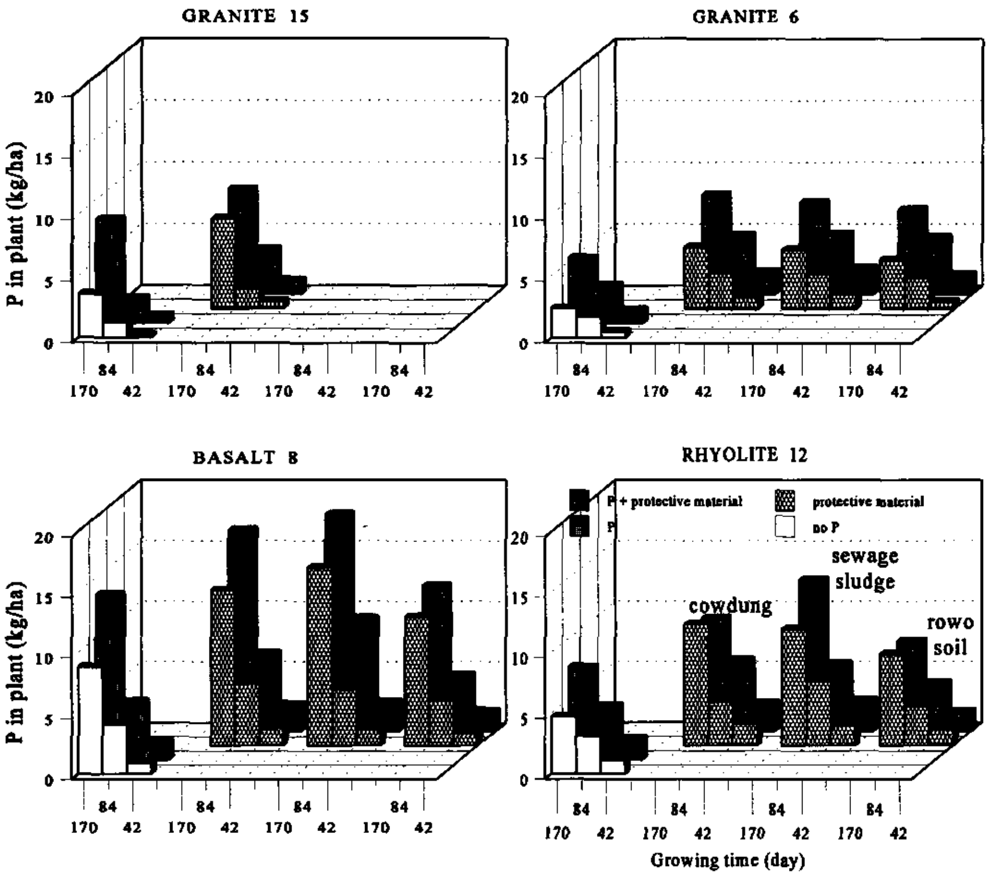


Figure 19. Relationships between P application rate and N concentration in the youngest full-grown leaf at 63 days after planting in the third season. a, b and c indicates increasing degrees of V-shaped yellowing in the older leaves.
a (1900 mmol/kg); b (1600 mmol/kg); c (1300 mmol/kg).

The experiments on Fields 2 and 11 were only due to be conducted until nine weeks after planting for plant height measurements and sampling. However, because of the excellent crop stand on Field 2, it was decided to continue the experiment on this field and to harvest the ears even though they had not matured at the time the project had to be terminated. At harvest, the grain moisture contents were about 40 %, so that the yields might have been higher than shown in Figure 13 if the crop had received time to mature. According to Aldrich et al. (1975), a further yield increase of 10 to 15 % can be expected at this growth stage.



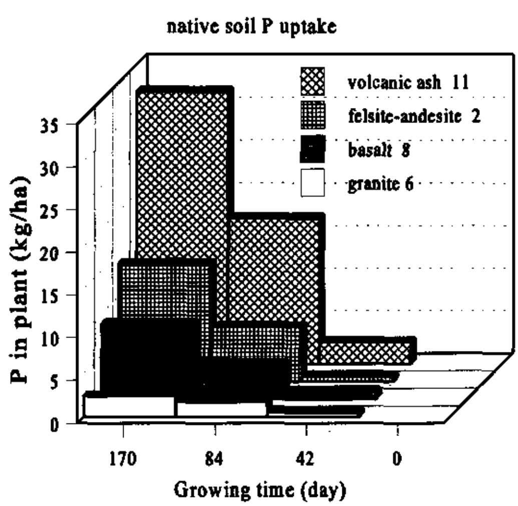


Figure 20. P present in above ground plant components before stalk elongation (42 days), after stalk elongation (84 days), and at maturity (about 170 days after planting). Treatments: subseed placement and protected placement; P rates: 0 and 22 kg/ha.

7.2 P UPTAKE AND UTILIZATION

7.2.1 P uptake during a growing season

During the second season, total P in plants was measured three times: just before and just after stalk elongation, and at harvest. It was observed that sizeable fractions of total P were still absorbed during and after stalk elongation for all treatments and on all soils (Figure 20). This means that the periods of vegetative and generative development are both important for P uptake, irrespective of the amount and method of P application or the nature of the soil.

Native P uptake rate and the total amount of native P taken up in plants varied among soils. They increased in the following order: granite (15, 6), rhyolite (12), basalt (8), felsite-andesite (2), volcanic ash (11). On the volcanic-ash soil, P uptake proceeded much more rapidly and total P uptake was much larger than on any other soil. These differences are in line with the observed control yields and confirm the conclusions drawn from these results in Chapter 7.1.1

In each period of plant growth, P uptake proceeded more rapidly with fertilizer P than without, so that differences in amounts taken up from fertilized and unfertilized plots gradually increased in the course of the season. Protection of fertilizer P in cow dung and sewage sludge further increased the P uptake rate while, with protection in Rowo soil, such an increase was found only on Field 6. As can be observed in Figure 20, this increase was mainly the result of an improved P uptake, caused by these protective materials themselves. This finding indicates that the effect of fertilizer P application and the effects of applications of cow dung, sewage sludge and Rowo soil on P uptake were mainly additive.

7.2.2 Distribution of P among the various plant components

7.2.2.1 *P distribution during a growing season*

The relative P distribution among plant components is shown in Figure 21, at about the beginning, the end of stalk elongation and at maturity. Since only leaves had developed at the beginning of stalk elongation, P was present only in this tissue at the first intermediate harvest. The amount of P in leaves further increased during stalk elongation, in which period leaf tissue fully developed. In the third period, in which flowering and kernel-filling took place, the amount of P in both leaves and stalks decreased considerably on most of the soils. This indicates that a portion of the P in these tissues is transferred to other tissues, mainly to grain.

Fertilizer P application hardly affected the relative amounts of P taken up at the beginning and at the end of stalk elongation and the distribution of P over leaves and stalks at the end of stalk elongation. However, it markedly increased the fraction of P stored in grain on soils underlain by granite (15, 6), rhyolite (12) and basalt (8). Especially in the case of protected subseed placement.

The fractions of total P absorbed at the first and second intermediate harvests varied to some extent among soils. This variation cannot, however, be attributed to differences in soil proper

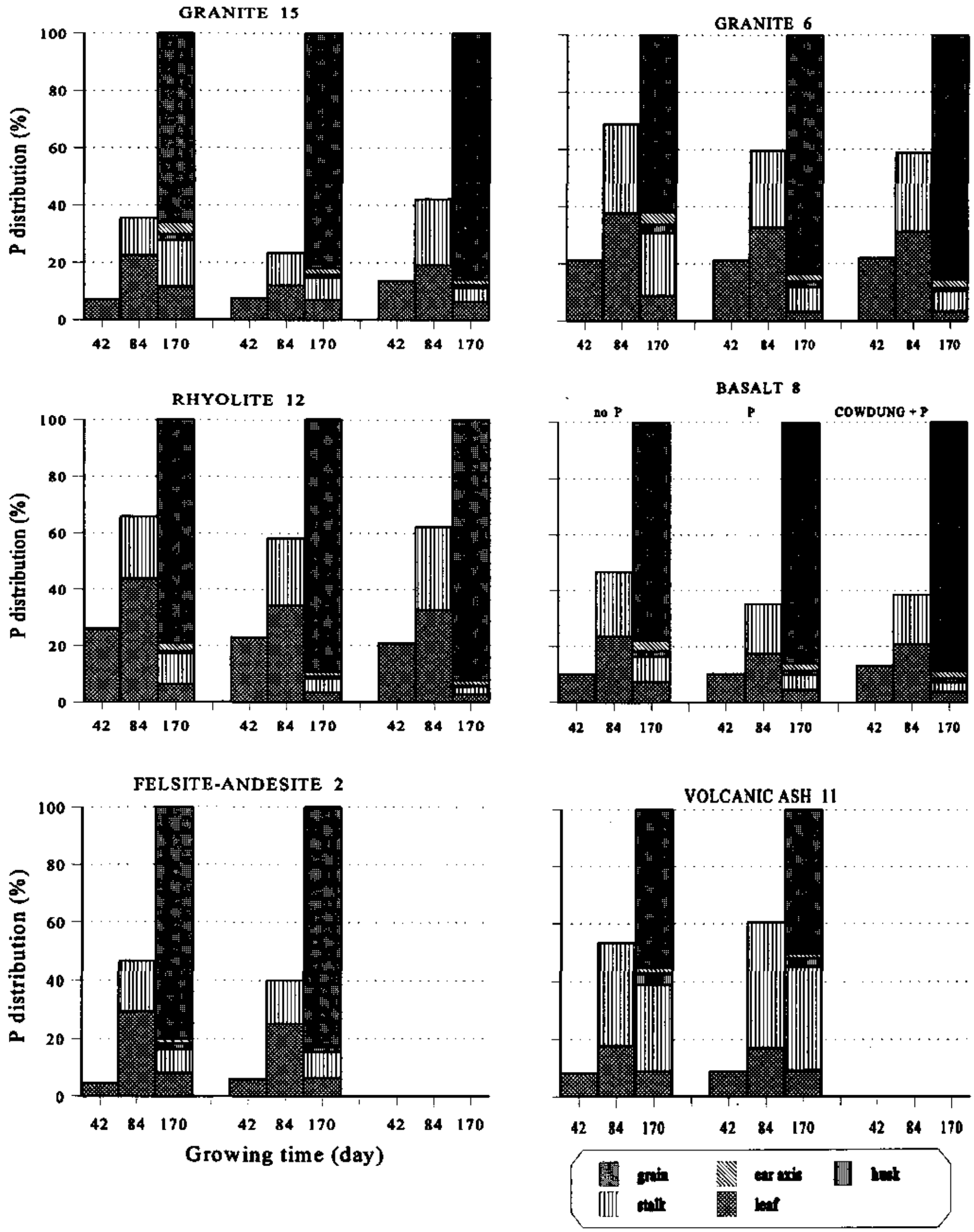


Figure 21. Relative P distribution over plant components before stalk elongation (42 days), after stalk elongation (84 days), and at maturity (about 170 days after planting). Treatments: no P, P placed at a rate of 22 kg/ha with subseed placement and protected subseed placement in cow dung.

ties only, as weather conditions also contributed. For example, since germination and early plant growth were faster on Field 12 than on Field 2, due to a higher soil temperature at the lower altitude where Field 12 was located, the fraction of total P absorbed up to the first intermediate harvest was large on Field 12 and small on Field 2. A second example can be observed in a comparison of the results for Fields 6 and 15. These were both located on granite soils and at the same altitude, so that comparable results could be expected. However, a hailstorm in an early stage of kernel-filling reduced grain production on Field 6 (Chapter 7.1.3) and, as no damages occurred to the plants on Field 15, the relative amounts of P absorbed up to the first and second intermediate harvest were high on Field 6 and low on Field 15.

In plants on the volcanic-ash soil (11), P distribution differed considerably from that on other soils. When stalk elongation was completed, much more P was found in stalks than in leaves, whereas on the other soils the ratio was about equal or reversed. The amounts of P in stalks and leaves were hardly reduced during kernel-filling and, as a result, the fraction of total P present in grains was small (about 50 %), whereas on the P-fertilized plots of the other soils it was about 85 %.

7.2.2.2 *Relationships between total P absorbed in plant and P storage in grain.*

To economize on crop sampling and analysis, an attempt was made to estimate total P in above-ground plant material from P present in grain. Henceforth "P in above-ground plant material" will be referred to as "P in plant".

The relationships between the two parameters for the various placement experiments initiated in the second season are shown in graph form in Figure 22 for four soils, and, presented mathematically in Table 6 for six soils. For each soil, the relationships turns out to be linear, which indicates that P-application and variations in method of placement did not affect the relationships. About identical equations were calculated for the five soils in which P was the yield-limiting factor at the P application rates used (see Chapter 7.1.2). Hence, the calculation of a general equation for these soils is justified. For the whole range of quantities of P stored in grain (0.9 to 17.8 kg/ha), the equation is $y = 0.46 + 1.13\ x$ (equation no. 7 in Table 6), in which (x) represents the amount of P present in grain and (y) the amount of P present in plant. This means that for this range, 61 to 87 % of P in plant was stored in grain. The equation of the line for the volcanic-ash soil (equation no. 6 in Table 6) differed from those of other soils. Here, P did not limit grain yield, so that the amount of P in grain was small (about 50 %) compared to that in plant (Figure 21 and 22).

It is justified to use the same equations for estimating P in plant for the experiments carried out with P mixed into the soil and applied at higher rates if similar relationships as mentioned above do exist. This was investigated for soils underlain by granite (15) and felsite-andesite (2) in experiments carried out in the first season.

On the granite soil (15), the estimates obtained with equation no. 2 and no. 7 in Table 6 were correct for placement at each P rate and for mixing up to a P rate of 524 kg/ha (Figure 23). Above this rate, production and partitioning of dry matter hardly changed, whereas, as a result

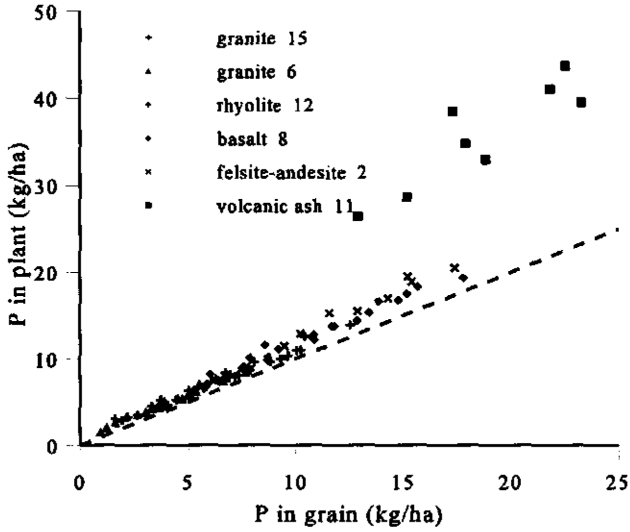


Figure 22. Relationships between P in above ground plant components and in grain for six soils. Each symbol represents a single measurement (second season). Treatments: subseed placement, protected subseed placement in cow dung, sewage sludge or Rowo soil and scattered placement). P rates: 0 and 22 kg/ha. [(--), P in plant/ P in grain = 1].

Table 6. Linear relationships between P (kg/ha) stored in grain(x) and P absorbed in plant(y) for six soils. Treatments: no P and P placed at a rate of 22 kg/ha (subseed placement, protected placement in cow dung, sewage sludge or rowo soil, and scattered placement), (see Figure 22).

Soil/ Parent material	Field no	Equation	Correlation coefficient(r)	Sample size	Interval of x	Equation no
Granite	15	y=0.90+1.06x	0.99	14	1.6 - 10.4	1
Granite	6	y=0.83+1.03x	0.99	20	0.9 - 7.7	2
Rhyolite	12	y=0.97+1.00x	0.99	22	2.7 - 12.5	3
Basalt	8	y=1.49+1.04x	0.99	20	5.3 - 17.8	4
Felsite/andesite	2	y=1.19+1.14x	0.98	8	9.5 - 17.4	5
Volcanic ash	11	y=7.91+1.49x	0.90	8	12.9 - 23.3	6
	15,6,12,8,2	y=0.46+1.13x	0.99	84	0.9 - 17.8	7
	15,6,12,8,2	y=0.79+1.07x	0.99	61	0.9 - 10.0	8
	15,12,8,2	y=0.06+1.17x	0.96	23	10.0 - 17.8	9

of luxury P consumption, P concentration increased more in stalk and leaf than in grain (Chapter 7.2.3.2). Consequently, P in plant was underestimated at this high application rate when the equations were used.

On the felsite-andesite soil (2), P in plant was underestimated with the use of equations no. 5 and no. 7 in Table 6 at each treatment. For the control and subseed placement treatments, it is suggested that the underestimation results mainly from lodging, which reduced setting and filling of grain in the first season (Table 7). Consequently, grain yields were low compared to total plant mass, and hence the amount of P in grain was low compared to P in plant. On plots with P mixed in, lodging decreased with increasing P application rate so that the observed underestimation at a P rate of 2,096 kg/ha could be ascribed to the same cause as mentioned for the granite soil.

Summarising, it can be said that for every season and all application methods accurate estimates of the amount of P absorbed in plant (y) could be obtained from the amount of P stored in grain (x) with the equation: $y = 0.46 + 1.13\ x$ if there was no lodging or luxury P consumption. The latter occurred on the volcanic-ash soils, and on the other soils, only at P application rates higher than 524 kg/ha. In these instances, P in plants was underestimated when the above mentioned equation was used.

Table 7. The effect of lodging on plant quality and ear formation for Field 2 in the first season. Each value is an average of three replicates. (Pl), number of plants damaged after flowering so that ears with kernels could not be formed. (Ecg), ears with more than 85 % of the sites occupied with kernels. (Ecp), ears with less than 85 % of the sites occupied with kernels. (Eb), ears without kernels (barren).

Treatment	P rate (kg/ha)	Number of lodged plants (%)	Plant quality Pl (%)	Ear quality Ecg (%)	Ecp (%)	Eb (%)
Control	0	78	33	26	10	3
Placement	44	60	16	41	6	1
Mixing	524	43	12	36	4	0
Mixing	2,096	20	6	45	3	1

7.2.3 P utilization in plants

7.2.3.1 *Yield-uptake relationships*

Figure 24 shows the relationships between P in plants and grain yields for six soils. The marks representing the results of the various placement experiments that were initiated in the second season matched a straight line fairly well in every diagram. This indicates that rate nor method of P placement affect these relationships.

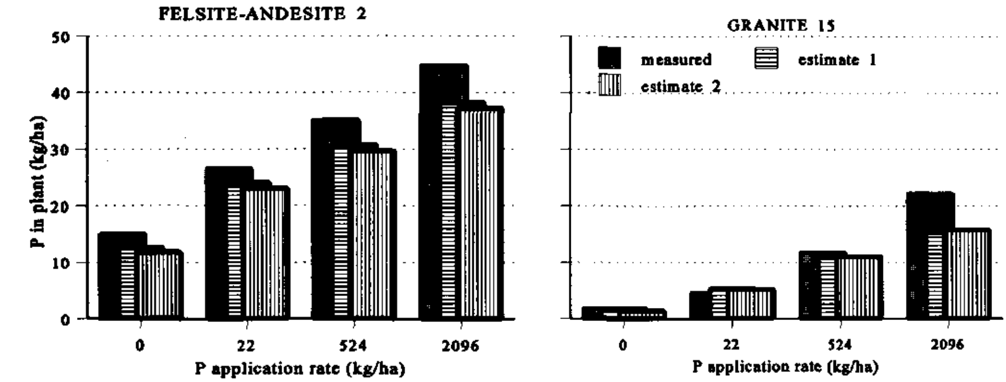


Figure 23. Comparison between estimated and measeured P in above-ground plant components. Estimates were calculated with the field equation (estimate 1) and the general equation (estimate 2) obtained with low P application rates in the second season (table 6, equation 7). Measured P data included high application rates and were obtained in the first season.

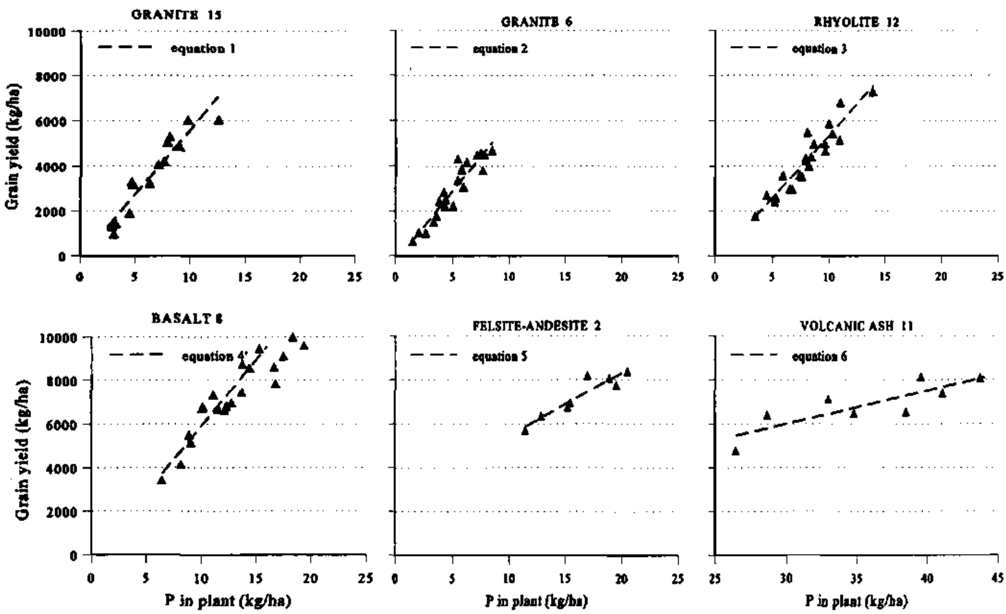


Figure 24. Relationships between P in above-ground plant components and grain yield for six soils. Each symbol represents a single measurement (second season). Treatments: subseed placement, protected subseed placement in cow dung, sewage sludge or Rowo soil, and scattered placement. P application rates: 0 and 22 kg/ha. Equations 1, 2, 3, 4, 5, and 6 refer to equations in Table 8.

For the granite(15,6), rhyolite(12) and basalt(8) soils, similar linear equations were calculated (Table 8), especially when overlapping ranges of P in plants were considered. This means that differences in soil properties did not affect the relationships when P was limiting grain yields (Chapter 7.1.2). At identical grain yield levels, slightly more P was absorbed in plants on the felsite-andesite soil(2) and much more on the volcanic-ash soil(11) than on the other soils. The equations show that, for producing grain, plants need a minimum quantity of P for building up their leaf and stalk tissues. This minimum quantity can be estimated by extrapolation.

For a reliable extrapolation, use was made of the experimental units of Fields 15, 6 and 12, where P in plants and grain yields were low, so that the extrapolation distance was short. As a useful range of P in plant 1.5 to 7.5 kg/ha was chosen. For this range, equation no. 8 in Table 8 shows the relationship. The minimum P quantity to be absorbed in plants to allow production of grain is estimated from this equation as 0.5 kg/ha. Using this minimum quantity and the data in the P in plant range of 1.5 to 11 kg/ha, the following general equation was derived: $z = 620(y - 0.5)$, in which (y) and (z) represent P in plant and grain yield respectively. This equation was used for evaluating the results of the experiments that were initiated in the first season and continued over three growing seasons, and in which P was either incorporated into the tilled layer or placed below the seed.
Similar equations were derived and used by Van Keulen & Van Heemst (1982) and introduced in the system for Quantitative Evaluation of the Fertility of Tropical Soils (QUEFTS) (Janssen et al., 1990; Smaling & Janssen, 1993).

Table 8. Lineair relationships between P in above-ground plant components(x) (kg/ha) and grain yield(y) (kg/ha) for six soils. Treatments were: no P and P placed at a rate of 22 kg/ha (subseed placement, protected placement in cow dung, sewage sludge or Rowo soil, and scattered placement), (See Figure 24).

Soil/ Parent material	Field no	Equation	Correlation coefficient(r)	Sample size	Interval of x	Equation no
Granite	15	y=580(x-0.31)	0.95	14	2.5 - 12.5	1
Granite	6	y=627(x-0.44)	0.94	20	1.5 - 8.5	2
Rhyolite	12	y=557(x-0.42)	0.94	22	3.5 - 14.0	3
Basalt	8	y=465(x+2.73)	0.93	20	6.5 - 19.5	4
	8	y=613(x-0.43)	0.94	15	6.5 - 16.0	4'
Felsite-andesite	2	y=285(x+9.08)	0.94	8	11.5 - 20.5	5
Volcanic ash	11	y=150(x+9.92)	0.84	8	26.5 - 44.0	6
	15,6,12,8	y=621(x-0.65)	0.95	60	1.5 - 11.0	7
	15,6,12,8	y=607(x-0.52)	0.88	33	1.5 - 7.5	8
	15,6,12,8	y=620(x-0.50)		61	0.5 - 11.0	9

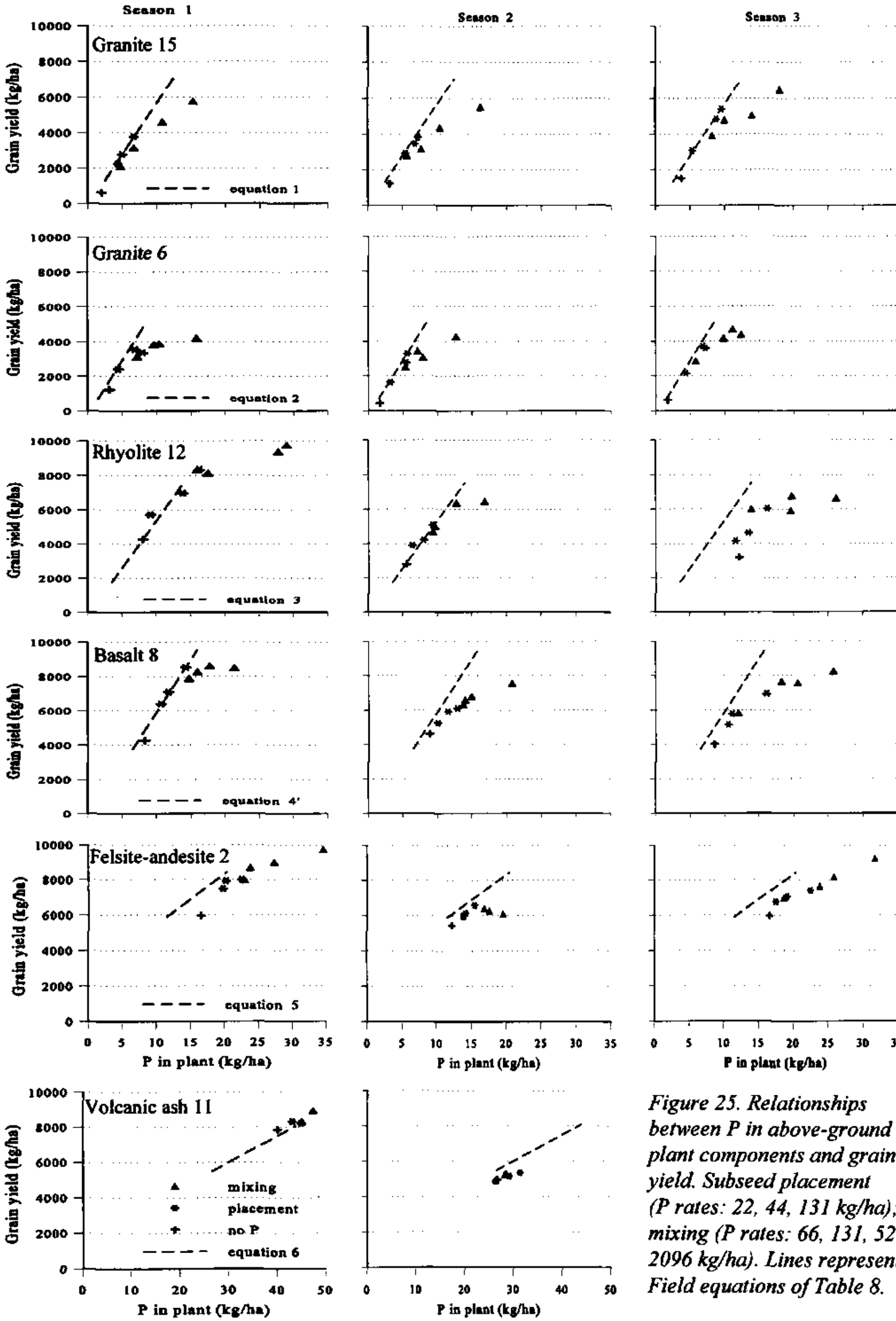


Figure 25. Relationships between P in above-ground plant components and grain yield. Subseed placement (P rates: 22, 44, 131 kg/ha); mixing (P rates: 66, 131, 524, 2096 kg/ha). Lines represent Field equations of Table 8.

Figure 25 shows the relationships between P in plant and grain yields for six soils in three seasons. In each diagram the corresponding field equations of Table 8 were drawn as dotted lines. Since the marks for placed and mixed fertilizer are well in line in each diagram, the efficiency of P utilization was more or less the same with placement and mixing at equal P in plant levels. On the granite soils(15,6) and the basalt soil(8), however, P placed below the seed was slightly more efficiently utilized, especially in the first season, than mixed fertilizer P at overlapping P in plant levels i.e. at overlapping P application rates. Most diagrams show that, at low levels of P in plant, the marks are close to the lines, indicating that P was efficiently utilized every season on each soil at those levels. With increasing P in plant, the marks remain close to the lines initially but, upon reaching near maximum grain yields the marks diverge from the lines, indicating a decreasing efficiency of P utilization.

Some seasonal variations in the efficiency of P utilization can be observed. Part of this variation was probably due to the fact that grain yields varied, especially the maximum yields, which were lower in the second than in the first season. As a result, marks diverge from the lines at lower grain yields (Field 12, 8, 2), they shift along the lines to lower yield levels (Field 11), they come together (Field 8), or they show all these characteristics (Field 2). In some diagrams, marks lay below the lines. On Field 12 (third season), Field 8 (second and third season) and Field 2 (first and second season) this was most likely caused by wind damage (Chapter 7.1.3). Due to lodging, setting and filling of kernels was disturbed, which resulted in low grain yields, although relatively large quantities of P had been taken up. Wind damage was most severe on Field 12 in the third season, which can be seen from the wide gap between the marks and the line. In the third season, grains were harvested prematurely on Field 2 (Chapter 7.1.3). At harvest, kernel-filling was not yet completed, so that P utilization was suppressed.

Since method and time of P application did not affect the efficiency of P utilization and seasonal effects were small, the results were summarized for each soil to obtain an average picture of the relationships between P in plant and grain yield over three growing seasons. Figure 26 shows the results for four soils. As long as P limited grain yield, P was efficiently utilized on the granite(6), rhyolite(12) and basalt(8) soils and fairly efficiently on the felsite-andesite(2) soil. It was not efficiently utilized on the volcanic ash(11) soil.

The efficiency of P utilization or, in other words, the grain yield/ P in plant ratio can be expressed by modifying the previous equation into: $z/y = 310/y + 620$.
Figure 27 shows the efficiency of P utilization in plants as a function of P in plant averaged over three seasons for six soils. On the volcanic ash soil(11), the efficiency of P utilization was low (<200 kg/kg), and not affected by P application. On the other soils, where native P limited grain yield, the efficiency first increased and reached maxima of over 500 kg/kg at P application rates of about 44 kg/ha and then gradually decreased to about 300 kg/kg at P application rates above 524 kg/ha. The initial increase was most clear on the granite soils(15,6) and the rhyolite soil(12). The maximum efficiencies for the soils were obtained at different P levels in plant. With increasing P in plant, they were reached in the following order: granite(6) < granite(15) < rhyolite(12) < basalt(8) < felsite-andesite(2).

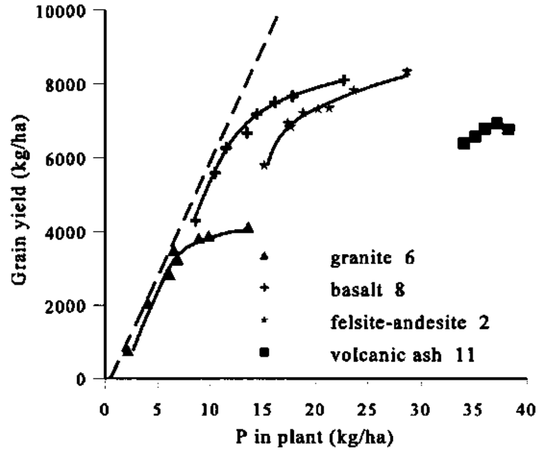


Figure 26. Relationships between P in plant and grain yield averaged over three seasons, except for volcanic ash where it was averaged over two seasons. Dotted line is based on the general equation no 9 in Table 8.

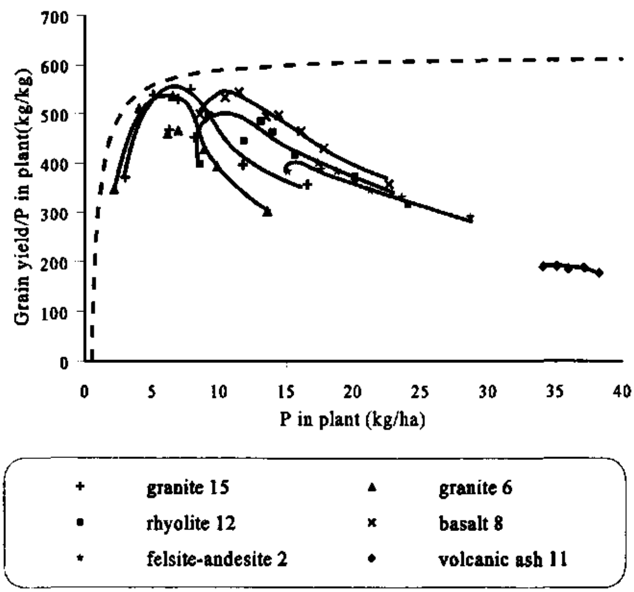


Figure 27. P utilization efficiency in relation to P in plant. Treatments: no P, subseed placement at P rates of 22, 44, 131 kg/ha, mixing at P rates of 66, 131, 524, 2,096 kg/ha. Data are average values of two (volcanic ash) or three seasons. Dotted curve is based on the general equation no 9 in Table 8.

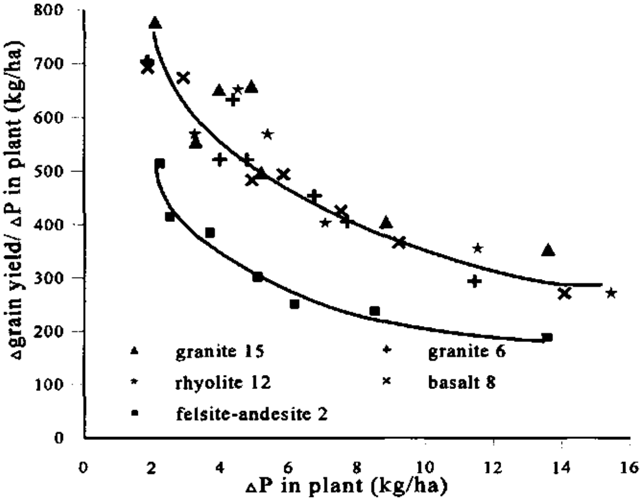


Figure 28. Apparent fertilizer P utilization (Δgrain yield/ΔP in plant) as function of ΔP in plant. Treatments: subseed placement at P rates of 22, 44, 131 kg/ha; mixing at P rates of 66, 131, 524, 2,096 kg/ha. Data are average values of three seasons.

The efficiencies of utilization of native soil P and fertilizer P were calculated with the equations given in Chapter 4.2 and are presented in Figure 27 for total P (native and fertilizer P) and in Figure 28 for fertilizer P. For native soil P, the efficiencies were: 348 kg/kg (granite 6), 371 kg/kg (granite 15), 398 kg/kg (rhyolite 12), 499 kg/kg (basalt 8), 383 kg/kg (felsite-andesite 2) and 190 kg/kg (volcanic ash 11). The efficiency of fertilizer P utilization was high at low levels of P in plant i.e. at low application rates. With increasing P in plant as a result of increasing application rates, the efficiency decreased to levels below those at which native soil P was utilized. At corresponding P in plant, the efficiency of fertilizer P was about equal for the granite soils(6), the rhyolite soil(12) and the basalt soil(8). On the felsite-andesite soil(2), fertilizer P was less efficiently utilized. Since, on the volcanic ash soil(11), P application did not result in a grain yield response and did not affect the efficiency of P utilization, the efficiency of fertilizer P utilization was not calculated.

7.2.3.2 *P concentration in plant components at maturity*

Figure 29 shows the P concentration in grain as a function of grain yield for six soils averaged over three seasons. In most diagrams, P concentration first decreased and reached minimum levels at P rates of 22 and 44 kg/ha. They then increased and reached the highest levels at a P rate of 2,096 kg/ha. Since the maximum grain yields varied among the soils, the highest P concentration levels were obtained at different grain yields. On the volcanic ash soil(11), P concentration was high and not affected by P application. For each soil subseed placement and mixing of fertilizer P resulted in about equal P concentrations at overlapping grain yields. However, where differences were observed the P concentrations in grain were slightly higher with mixing than with subseed placement. Seasonal variations in P concentration levels were small (Appendix 6). On most soils, P concentrations were slightly lower in the second season than in the first and third season. Part of the seasonal variation probably resulted from lodging (Chapter 7.1.3).

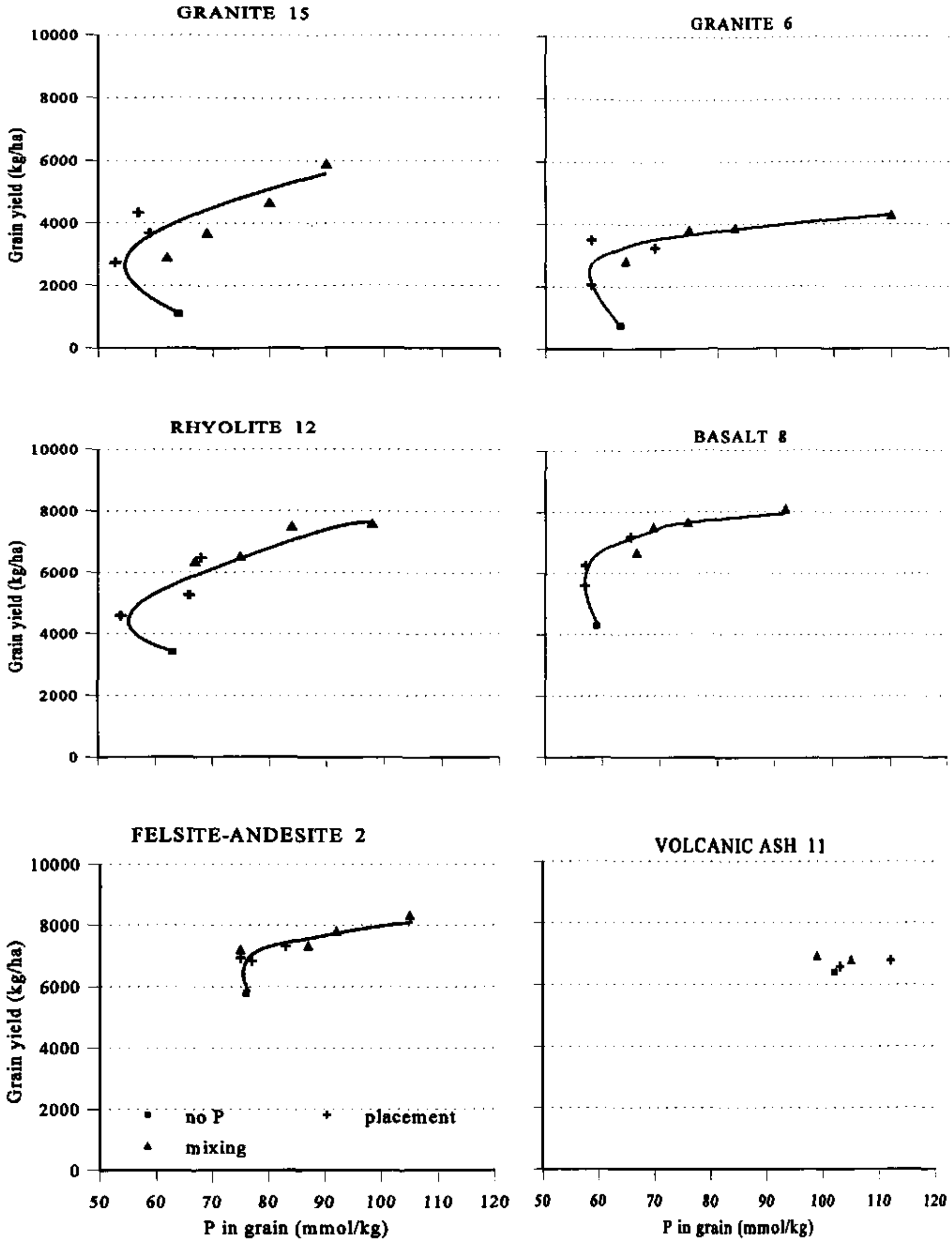


Figure 29. Relationships between P concentration in grain and grain yield. Data are average values of three seasons. P application rates were 22, 44, 131 kg/ha with subseed placement and 66, 131, 524, 2096 kg/ha with mixing.

When the shapes of the response curves of Figure 13 are taken into account, it can be said that as long as P limited grain production, P concentration in grain increased with increasing P rates. This increase continued beyond P rates at which the yield response curves had already levelled off. This indicates that, with increasing P rates, fertilizer P was utilized first for producing more grain with a low P concentration and on approaching maximum yield levels it was utilized for producing grain with a high P concentration.

P concentration in grain varied among soils with respect to the minimum levels (Table 9). On the granite soils(15,6), rhyolite(12) and basalt soil(8) the minimum P concentration, averaged over three seasons, was about 55 mmol/kg (1.7 g/kg), whereas on the felsite-andesite soil(2) it was 75 mmol/kg, and on the volcanic ash soil(11) about 100 mmol/kg. The highest P concentrations in grain were fairly similar for each soil. They were about 100 mmol/kg (3.1 g/kg). Since this level was reached when P was not limiting grain yields due to a heavy fertilizer P application or a high native P availability, 100 mmol/kg is assumed to be a maximum P concentration value for grain.

Table 9. Lowest and highest P concentration levels in grain for six soils. Data are average values per treatment over three seasons, except for Field 11 where they are averaged over two seasons.

Soil/ Parent material	Field no	Lowest P concentration (mmol/kg)	Highest P concentration (mmol/kg)
Granite	15	53	90
Granite	6	56	110
Rhyolite	12	54	98
Basalt	8	57	92
Felsite-andesite	2	75	105
Volcanic ash	11	101	111

P concentrations in grain, ear axis, husk, stalk and leaf for different rates and methods of P application are given in Table 10 and are presented as a function of grain yield in Figure 30. P concentration first decreased and reached minimum levels at P rates of 22 or 44 kg/ha. They remained at a minimum level up to a rate of 2,096 kg/ha for ear axes, above 524 kg/ha for husks and stalks and about 524 kg/ha for leaves. For grains they had markedly increased at a P rate of 524 kg/ha and, as was shown in Figure 29, this increase had already started at a lower application rate. These results indicate that, as long as P limited grain yields, P concentration reached minimum levels in all plant components and that as soon as other factors started limiting grain yields, P first accumulated in grain up to a level of about 75 mmol/kg. Above this level, the P concentrations increased in other plant components in the following order: leaf > stalk > husk > ear axis.

Table 10. Relationships between P application rate (kg/ha) and P concentration (mmol/kg) in plant components of mature plants for four soils. Data are average values of three replicates unless denoted as (a) and (b) which refer to two and one replicate respectively. (*), with application of: K, Mg, S, Zn, Cu, Mo and B. The results were obtained in the first season.

Soil/ Parent material	Field no	Plant component	P application rate (kg/ha)					
			0	22	44	524	524*	2,096
				Placement		mixing		
Granite	15	Ear axis	29	15	13	16	13	19
		Husk	18	12	8	10	9	31
		Stalk	14	9	8	12	9	43
		Leaf	24	20	19	27	20	65
		Grain	62	53	59	75	84	85
Felsite-andesite	2	Ear axis	10	12	6	13	14	13
		Husk	18	16(b)	13(b)	21	25(b)	36
		Stalk	24	11(b)	24(b)	26	41(b)	40
		Leaf	28			38		52
		Grain	83	80	78	94	104	111
Granite	6	Stalk	11(a)	24(a)	17(a)	18(a)	42(a)	102(a)
		Grain	67	66	62	87	105	127
Rhyolite	12	Stalk	16	11	12	30		89
		Grain	61	52	67	105	98	105

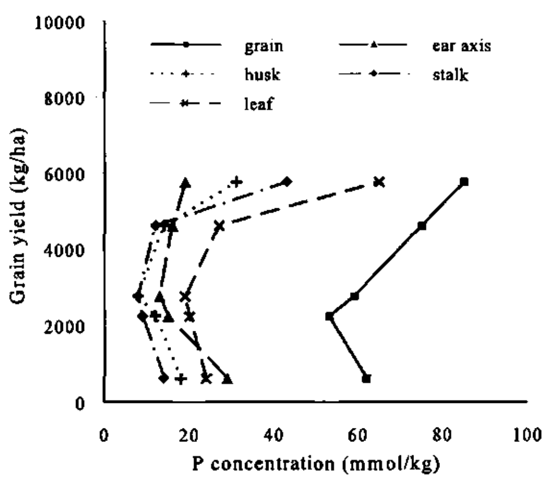


Figure 30. Relationships between P concentration in plant components and grain yield for the granite soil (15) in the first season. Treatments: no P, subseed placement at P application rates of 22, 44 kg/ha, mixing at P application rates of 524 and 2096 kg/ha.

For the six main fields, the lowest P concentration in grain, ear axis, husk, stalk and leaf were obtained from the placement experiments that were initiated in the second season during which P was placed below the seeds at a P rate of 22 kg/ha. The P concentrations in ear axis, husk, stalk and leaf were about 10 mmol/kg (0.3 g/kg). The P concentration in plant components were about equal for the granite(15,6), the rhyolite(12) and the basalt(8) soils (Table 11). On the felsite-andesite soil(2), they were slightly higher in leaf and grain, while on the volcanic ash soil(11) they were markedly higher in every plant component than on the other soils.

Table 11. Lowest P concentrations (mmol/kg) in plant components of mature plants for six soils. P was subseedly placed at a rate of 22 kg/ha. Data are average values of four replicates.

Soil/ Parent material	Field no	Plant component				
		Ear axis	Husk	Stalk	Leaf	Grain
Granite	15	9	5	10	17	57
Granite	6	8	7	10	5	45
Rhyolite	12	7	6	6	10	60
Basalt	8	14	6	9	14	56
Felsite-andesite	2	7	9	14	26	71
Volcanic ash	11	27	40	119	73	102

7.2.3.3 *P concentration in plant components during a growing season*

The P concentrations in leaf and stalk as a function of growing-time are shown for six soils in Figure 31. They decreased in time on each soil except for stalks on the volcanic ash soil(11). Since the first and second measurement coincided with the start and completion of stalk elongation, the initial decrease in P concentration in leaf must have resulted mainly from dilution, whereas after stalk elongation it must have resulted from redistribution of P from leaf and stalk to other tissues, mainly to grains. The P concentrations were about equal on the granite(15,6), the rhyolite(12) and the basalt(8) soils. They were slightly higher on the felsite-andesite soil(2) and much higher on the volcanic ash soil(11).

The P concentration in the youngest full-grown leaf at nine weeks after planting as a function of P application rate, is shown in Figure 32. The P concentrations increased with an increasing application rate in the first and third season on all soils except on the volcanic ash soil(11), where they only increased in the first season. At low P application rates, P concentrations were about equal in both seasons. At high P application rates P concentrations were higher in the first than in the third season. At a P rate of 2,096 kg/ha very high P concentrations were found on the granite soils(15,6), where they were even higher than on the volcanic ash soil(11). The results of the first season may have been influenced by the previous severe drought, which was more severe on the Fields 15 and 6 than on the other fields (Chapter

7.1.3). Since the marks representing subseed placement and mixing are well in line in each diagram, it is concluded that the method of application did not affect the P concentration in the youngest full-grown leaf at nine weeks after planting.

The P concentrations in the youngest full-grown leaf at nine weeks after planting were compared with the P concentration of the entire leaf tissue in Figure 31 at an equal P application rate of 22 kg/ha. Since the marks are close to the lines for each soil, it is concluded that P concentration in the youngest full-grown leaf at nine weeks after planting gives a reliable indication of the P status of the plant at that stage of vegetative development.

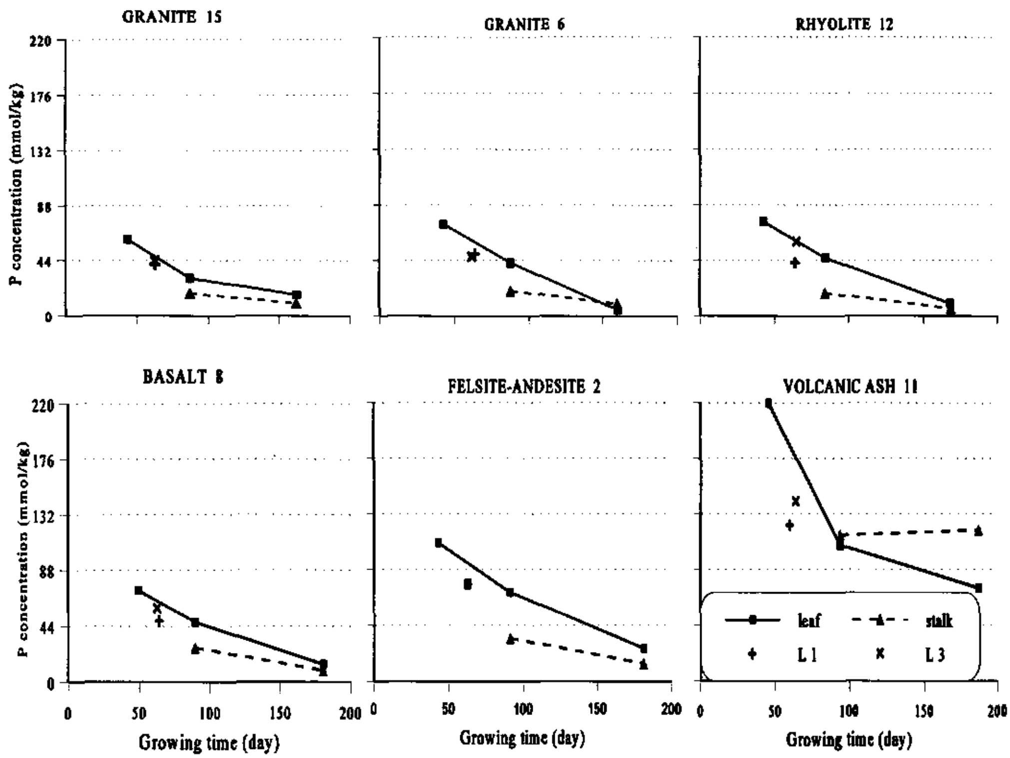


Figure 31. P concentration in leaf and stalk as function of growing time in second season and P concentration in youngest full-grown leaf at 63 days after planting in first (L1) and third (L3) season. Treatment: subseed placement at a P rate of 22 kg/ha.

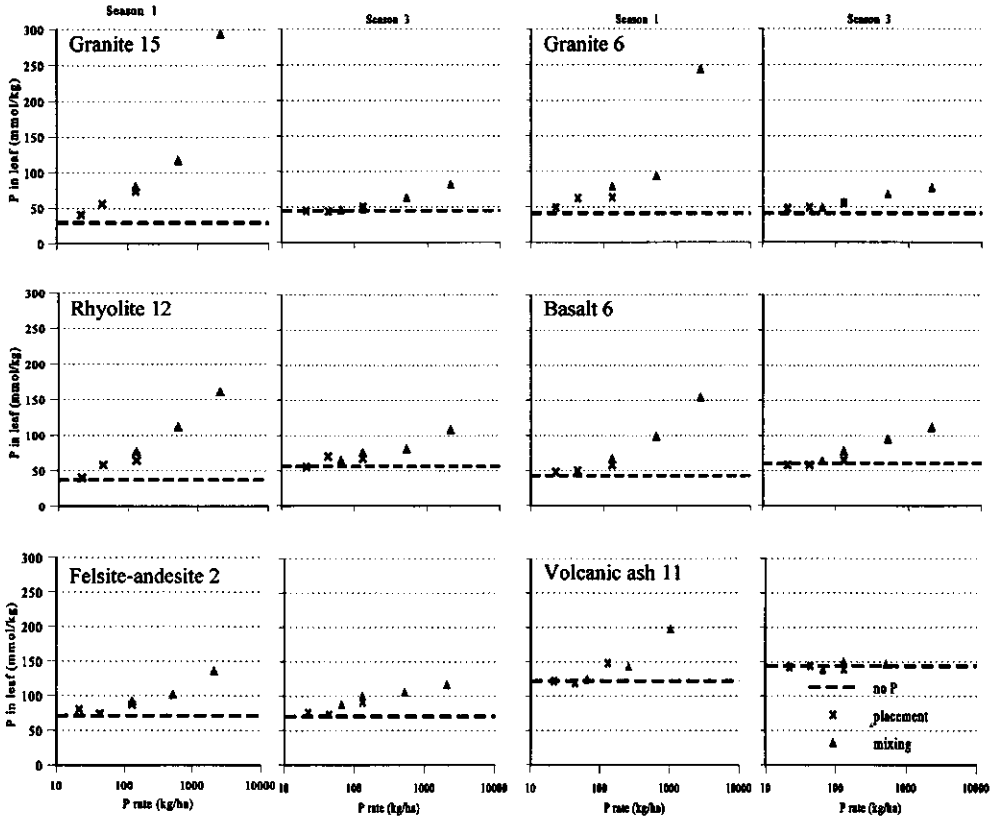


Figure 32. P concentration in the youngest full-grown leaf at 63 days after planting in relation to the P application rate. Season 1: initial response; Season 3 : residual response. Data are average values of two replicates.

7.2.4 Recovery of fertilizer P in plants

Fertilizer P apparently recovered in above-ground plant components (ΔP in plant) is shown as a function of the P application rate in Figure 33 for five soils, separately for each season and cumulated over three seasons.
The amount recovered increased more or less parabolically with an increasing P application rate. Subseed placement and mixing resulted in about equal recovered amounts at overlapping rates. The amounts recovered were about equal each season, which means that irrespective of the fertilizer P present as fresh or residual fertilizer, plants recovered a more or less constant amount of fertilizer P each season. The amounts recovered hardly differed among the soils, which indicates that differences in soil properties, for instance in P-sorption capacity, did not affect the P recovery.

The fraction of P recovered from the fertilizer (P recovery) can be read from Figure 33 (dotted lines). It varied from about 0.25 at the lowest application rate (22 kg/ha) to 0.02 at the highest application rate over three seasons, which is about 0.082 to 0.007 per season.

When using the P recovery data, one should be aware of the large relative error in these data and the fact that this error increases with a decreasing P application rate as a result of a decrease in ΔP in plant and a concomitant decrease in grain yield response. On the other hand, the amount of P in the above-ground plant components is underestimated at high P application rates, where luxurious P consumption occurred and thus P recovery was underestimated (Chapter 7.2.2.2).

From the results of the various placement experiments that were initiated in the second season, P recoveries could be estimated at very low application rates. Table 12 shows that the average recovery decreased from 0.38 to 0.11 per season for P application rates ranging from 5.5 to 22 kg/ha.

Table 12. Apparent fertilizer P recovery (%) in plants for subseed placement over two growing seasons. P in plant was estimated with the field equations of Table 6.

Soil/ Parent material	Field no	P rate (kg/ha) 5.5	11	22
Granite	15		54	36
Granite	6		20	21
Rhyolite	12	113	51	34
Basalt	8	57	36	31
Felsite-andesite	2	56		34

Protection of fertilizer P in cow dung, sewage sludge or Rowo soil did not increase the P recovery when compared with unprotected subseed placement, neither at a P rate of 22 kg/ha

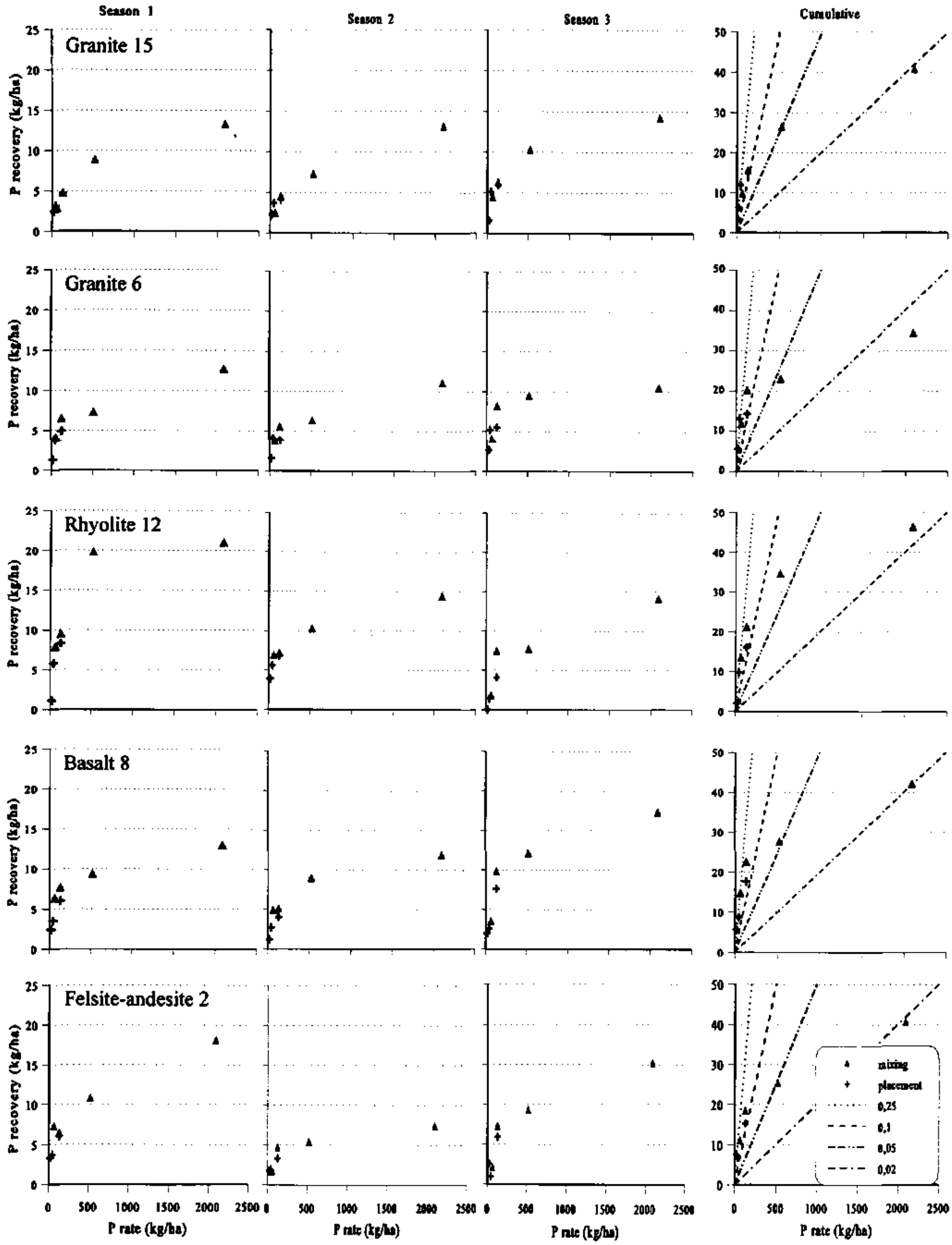


Figure 33. Fertilizer P recovery in above-ground plant components and cumulative P-recovery fractions over three seasons as function of P application rate.

nor at a rate of 11 kg/ha (Table 13).

With scattered and deep placement, the P recoveries were not higher than with subseed placement at an equal P application rate of 22 kg/ha (Table 14).

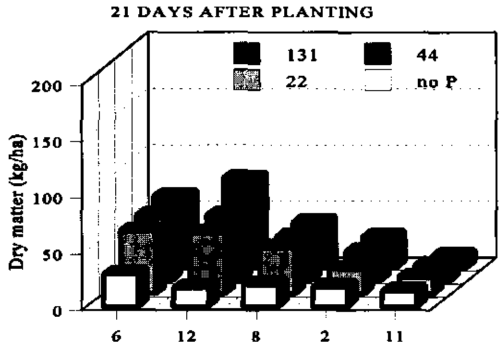
Table 13. Apparent fertilizer P recovery (%) in plants over two seasons for protected and unprotected subseed placement. P in plant was estimated with the field equations of Table 6.

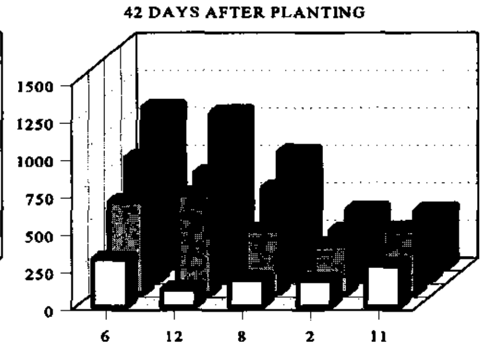
Soil/ Parent material	Field no	Unprotected placement		Protected placement					
				Cow dung		Sewage sludge		'Rowo' soil	
		P rate (kg/ha)		P rate (kg/ha)		P rate (kg/ha)		P rate (kg/ha)	
		11	22	11	22	11	22	11	22
Granite	15	54	36	50	24				
Granite	6	20	21	16	24	7	10	10	16
Rhyolite	12	51	34	30	17	29	9	10	5
Basalt	8	36	31	34	33	8	16	11	19

Table 14. Apparent fertilizer P recovery (%) in plants over two seasons for subseed placement, scattered placement in two and four holes, and deep placement. P rate was 22 kg/ha. The experiments were started in the second season. P in plant was estimated with the field equations of Table 6.

Soil/ Parent material	Field no	Subseed	Scattered two holes	four holes	Deep two holes
Granite	15	36	38	34	26
Granite	6	21	28	24	9
Rhyolite	12	34	34	38	31
Basalt	8	31	31	19	25
Felsite-andesite	2	34	16	11	18

N.B. P concentrations in grain for scattered placement and deep placement in the third season on Fields 6, 12, 8 and 2 were estimated on the basis of the measured P concentrations in grain in the second season and of those of Field 15 in the third season.





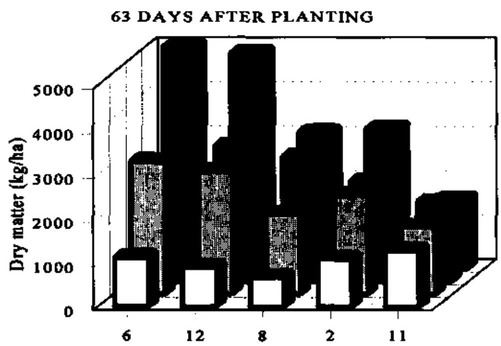
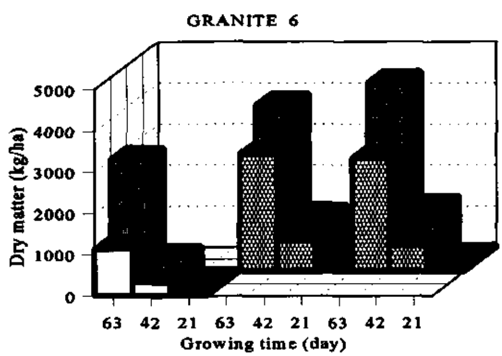
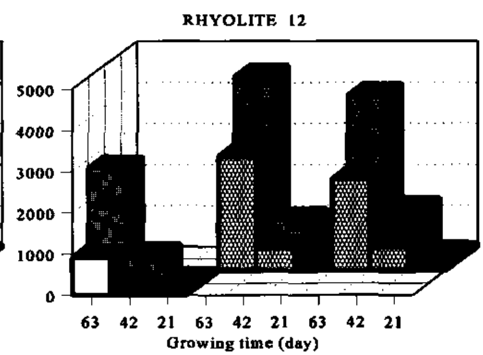


Figure 34. Dry matter production at 21, 42 and 63 days after planting. Treatments: no P, subseed placement at P rates of 22, 44 and 131 kg/ha. Number along the X-axis refer to the fields: granite 6 (1,550), rhyolite 12 (1,430) , basalt 8 (1,720), felsite-andesite 2 (1,900), volcanic ash (1,860). Numbers in parentheses refer to the altitude of the fields in meters above sea level. (Data: see Appendix 7).





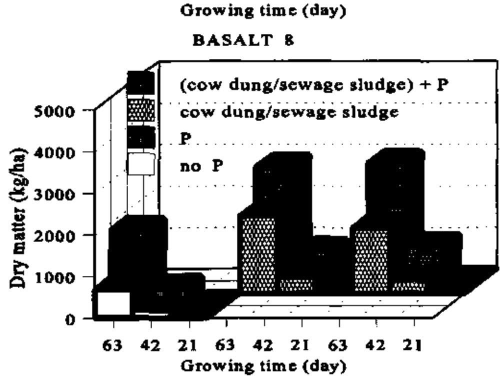


Figure 35. Dry matter production at 21, 42 and 63 days after planting. Treatments: subseed placement and protected subseed placement in cow dung or sewage sludge respectively. P application rates: 0 and 22 kg/ha. (Data: see Appendix 7).

7.3 EARLY PLANT RESPONSE TO P APPLICATION

7.3.1 Plant development

The early plant response, the starter effect, of placement of triple superphosphate was studied in the third season by measuring a number of plant properties indicating the stage of plant development at 21, 42 and 63 days after planting. The parameters were: plant height, plant diameter at the base of the stem, number of leaves, leaf width, height of the growing point, number of whorls in root crown, number of permanent roots, number of roots per whorl, root diameter and the above-ground dry matter production. Appendix 7 shows the results for subseed placement, protected subseed placement in sewage sludge and cow dung, scattered placement and deep placement.

Subseed placement

At 21 days after planting clear responses in plant height, plant diameter, leaf width, number of permanent roots and dry matter production were already observed on the granite(6), rhyolite(12), basalt(8) and the felsite-andesite soil(2). On the rhyolite soil, where soil temperature apparently favoured germination and early growth more than on the other fields, plant development was observed to have been already promoted by P application at 14 days after planting, which was about 7 days after germination. The responses gradually increased with time and at 63 days after planting large responses were measured with respect to these plant properties. At that time, the fertilized plants had also formed more leaves, more permanent roots in the later developed whorls, slightly more root whorls, thicker roots and more elongated stalks than the non-fertilized plants. These responses indicate that native P was growth limiting from the very beginning of the growing season.

An exception was formed by the volcanic ash soil(11) where, due to a high availability of native P, plant development was not limited by P in the non-fertilized plants. The relatively slow plant development on this field resulted from relatively low soil temperature. This also affected plant development on the other High-Altitude Fields 2 and 8 (Figure 34).

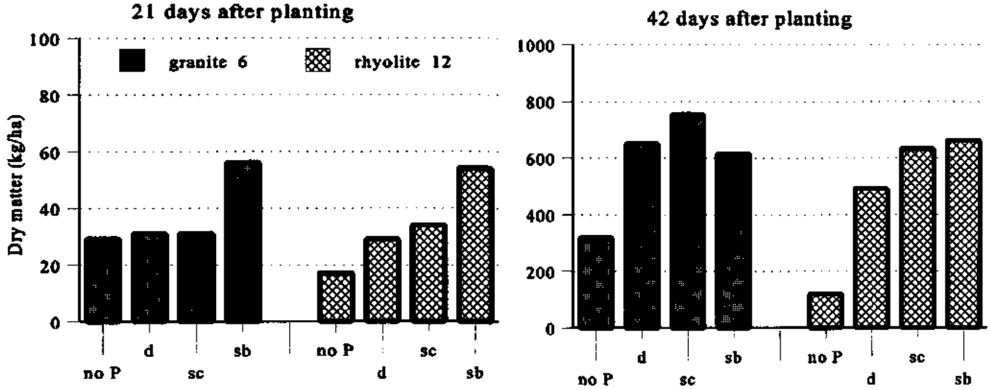
At 42 days after planting, a difference in plant development and in dry-matter production was observed as a result of differences in P application rates. This difference in response increased with time. Since it had not been observed, or only to a small extent, at 21 days after planting, it can concluded that, from about 21 days after planting, fertilizer P was no longer sufficiently available to maintain a maximum rate of plant growth with subseed placement at P rates of 22 and 44 kg/ha.

Protected subseed placement

Protected subseed placement improved plant development. This improvement resulted from the protective materials themselves (Figure 35). The response of sewage sludge and cow dung was already observed at 21 days after planting and gradually increased with time.

Scattered and deep placement

Until about 21 days after planting, plants did not respond to scattered and deep placement of



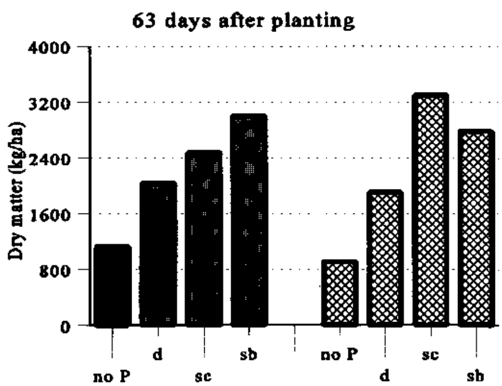


Figure 36. Dry matter production at 21, 42 and 63 days after planting. Treatments: no P, deep placement (d), scattered placement (sc) and subseed placement (sb). P application rate: 22 kg/ha (Data: see Appendix 7).

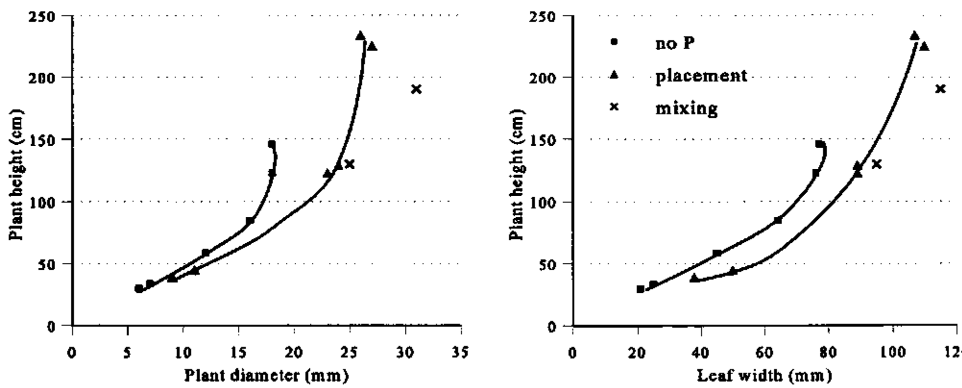


Figure 37. Relationships between plant height and plant diameter and between plant height and leaf width in developing maize plants. Treatments: no P, subseed placement at a P application rate of 131 kg/ha and mixing at a rate of 2,096 kg/ha. Measurements: 21, 42 and 63 days after planting on the granite (6) and rhyolite soil (12). (Data: see Appendix 7).

fertilizer P on the granite soil(6), while on the rhyolite soil(12) the responses in plant development and dry-matter production were small (Appendix 7 and Figure 36).

At 42 days after planting a marked response had developed on both soils. This was further increased at 63 days after planting. At 42 days after planting, the responses to scattered and subseed placement were equal and they developed similarly during the rest of the growing season (Figure 16). This indicates that the response with scattered placement developed more slowly up to about 21 days after planting and more rapidly between 21 and 42 days after planting than with subseed placement. Thus, fertilizer P placed beside a plant hole was less utilized up to 21 days after planting and better utilized from 21 to 42 days after planting than P placed in a plant hole.

With deep placement, plant development and dry-matter production at 63 days after planting still lagged behind that of subseed placement at an equal P rate. Thus, deep-placed fertilizer P beside a plant hole was hardly utilized up to 21 days after planting and, afterwards, not better utilized than P placed in a plant hole.

Other remarks

Dry-matter production increased exponentially after germination (Figure 35). At 63 days after planting, the amount of dry matter produced at a P rate of 131 kg/ha was about 4 times the amount produced by the non-fertilized plants. Dry-matter production proceeded at a rate of about 200 kg/ha.day, while it was about 50 kg/ha.day for the non-fertilized plants.

The P-induced acceleration in plant development led to an earlier stalk elongation, flowering and maturing, and hence to a shortening of the growing period (Photograph 2). At high application rates, the growing period was shortened by about one month, which was about 15 % of the period.

Although it is not within the scope of this study to present the relationships between the various plant parameters indicating the stage of development of which data are given in Appendix 7, it is of interest to discuss a few relationships. Figure 37 shows that, at equal plant heights, fertilized plants had formed thicker stalks and wider leaves than non-fertilized plants. For a reliable estimation of dry-matter production and a reliable prediction of grain yield during vegetative development, the results can be probably improved when based not only on one parameter, for instance plant height at a chosen time after planting, but on a combination of parameters, for instance of plant height and plant diameter at the base of the stem or of plant height and leaf width.

7.3.2 Root development

7.3.2.1 *In soils*

21 days after planting

At 21 days after planting, the seminal roots, i.e. the radicle and two or three other seminal roots had grown downwards and branched intensively in each soil. Six to fourteen permanent roots from two or three whorls had emerged from the crown (Appendix 7). They had radiated horizontally from the crown and, at some distance from the plants, they had gradually curved downwards. After reaching a length of about 15 cm they had started branching near the root base. As long as they were elongating, the distance between root tip and branching zone was maintained at about 15 cm. The permanent roots of the first whorl were most developed. They had reached a length of about 30 cm on the volcanic ash soil and about 60 cm on the granite and rhyolite soils. This difference was related to soil temperature, which differed among the fields as they were located at different altitudes (Chapter 7.3.1).

The root distribution patterns in the different soils were fairly similar at this early stage of growth, when roots were still mainly present in the freshly-tilled layers with equally loose soil structures. Root penetration in the soil below the tilled layer differed among the soils. It decreased in the following order: volcanic ash(11) > felsite-andesite(2) > basalt(8) > rhyolite(12) > granite(6). Roots penetrated easily on the volcanic ash soil, whereas they failed on the granite soil.

42 days after planting

At 42 days after planting, the number of permanent roots ranged from fifteen to thirty-two and the number of whorls from four to six. The differences were related to P application and soil temperature.

Since the permanent roots emerging from successive whorls are arranged spirally, they spread in all directions. The older ones of the first and second whorl had apparently reached their full-length: 100 to 135 cm in a lateral direction. Lengths of lateral roots were about equal for fertilized and non-fertilized plants. All these roots showed a similar branching pattern. Although equal in length, the roots of the non-fertilized plants were clearly thinner all over than the roots of the fertilized plants on the granite, rhyolite, basalt and felsite-andesite soils. When the plants were adequately supplied with P, roots were equally thick on all soils.

The vertical root growth was similar for fertilized and non-fertilized plants, but it varied largely among the soils. The number of roots that had penetrated in the subsoil decreased in the following order: volcanic ash(11) > felsite-andesite(2) > basalt(8) > rhyolite(12) > granite(6).

On the volcanic ash soil, root distribution was apparently not affected by the soil structure of the subsoil. The permanent roots of each whorl had gradually curved downwards and had passed the lower border of the tilled layer without any distortion and grew downwards, being hardly diverted by the soil aggregates. They had grown as though they were spokes in an opened umbrella. They had reached a depth of 100 to 120 cm. On the other soils, the structure of the subsoil, particularly just below the tilled layer and in the B-horizon, affected vertical root growth and so root distribution in the soil.

Although a large fraction of the roots on the felsite-andesite soil was present in the tilled layer, many roots had still penetrated the subsoil. A few had reached a depth of 130 cm, while being only slightly diverted by soil aggregates. Here, the A-horizon extended to below the tilled layer and the B-horizon had a moderate structure with friable, porous, fine subangular blocky aggregates. Appendix 8 gives the soil-profile descriptions.

On the basalt soil, a larger fraction of the roots than on the felsite-andesite soil was present in the tilled layer because of a shallower A-horizon and a more strongly structured B-horizon. The B-horizon consisted of medium angular blocky aggregates with continuous moderately thick clay cutans. In this subsoil, roots had penetrated easily. Most of them followed the inter-aggregated pores. A few roots had reached a depth of about 100 cm.

On the rhyolite soil, most of the roots were concentrated in the tilled layer and only a few had penetrated the subsoil. The maximum rooting depth was about 85 cm. Here, the strongly structured B-horizon consisted of firm, very fine, angular blocky aggregates with continuous clay cutans. Although single aggregates had many very fine pores, the number of fine and medium pores was small.

On the granite soil, almost all roots were concentrated in the tilled layer. Main roots curving downwards were diverted in the transition zone of tilled layer and subsoil. Most of them diverted laterally and continued growing just above the compact subsoil. A few roots of the fourth and fifth whorls and branches of the earlier developed roots had penetrated the subsoil, but were highly distorted. They had formed wavy-like curves and had branched more than usual. They had ended abruptly without reaching their normal length and were slightly thickened at the end. The maximum rooting depth was about 35 cm. Here, the soil just below the tilled layer was more compact than on the other soils. It consisted of strongly-structured, very fine, angular, blocky aggregates, which were firm when moist and hard when dry and had few fine and large pores.

<u>63 days after planting</u>

At 63 days after planting, the number of permanent roots ranged from twenty-seven to fifty six and the number of root whorls from six to eight. The numbers were related to P application and soil temperature. The characteristic root distribution patterns described for 42 days after planting were now more pronounced. In each soil, the main roots of the first four to six whorls had branched intensively all over, so that the entire tilled layer was rooted intensively. Root intensities in the subsoils decreased in the order mentioned at 42 days. The maximum rooting depths were: 135 cm (volcanic ash), 145 cm (felsite-andesite), 150 cm (basalt), 95 cm (rhyolite), 80 cm (granite). On the granite and rhyolite soils, these depths were reached due to the local presence of large, continuous, vertical biopores. Where these were absent, the rooting depths were about 45 to 60 cm on the rhyolite soil and about 40 cm on the granite soil.

For every soil and treatment, the seminal roots were still alive at 63 days after planting. (In a small experiment, it was found that plants from which the roots were cut off, except for the seminal roots, wilted later than when all roots were cut off). Since seminal roots were present at the site of the placed fertilizer, they were probably still involved in the absorption of fertilizer P at this stage of plant growth.

After 63 days after planting, new root whorls still developed. The roots of these whorls, particularly the youngest developed whorl of brace roots, grew more vertically than the earlier developed roots.

7.3.2.2 *Near fertilizer granules*

21 days after planting

Since seminal roots grow rapidly downwards, the chance of them reaching the fertilizer placed below the seed immediately after germination is high, especially for the radicle. One or more seminal roots had always passed the fertilizer site shortly after germination. For the P application rates of 44 and 131 kg/ha, the seminal roots and their branches that had penetrated the soil immediately surrounding the fertilizer granules were grey-brown at their tips and had died. If all seminal roots had entered the soil immediately surrounding the fertilizer, seedlings had died. This happened sometimes, especially at a P rate of 131 kg/ha. If only one seminal root had passed the fertilizer at a distance of a few centimetres, then the seedlings survived. At a P rate of 22 kg/ha, root tips were rarely burnt. Here, the downward-growing seminal roots were able to pass the bottom of the former cylindrical plant hole without noticeable damage, because the single fertilizer granules were situated apart from each other at the bottom of the plant hole. At P rates of 44 and, especially, at 131 kg/ha, the fertilizer granules were conglomerated at the bottom of the plant hole.

Immediate contact between fertilizer granules, either singly or conglomerated, and roots was not observed. This indicates that the response in plant growth at 21 days after planting (Chapter 7.3.1) resulted from fertilizer P that had dissipated into the soil up to some distance from the granules.

Roots had easily penetrated the strongly-structured fine sewage sludge and had branched profusely in this material, so that here root density was higher than at a similar position below a non-fertilized plant and higher than in the surrounding soil. Cow dung was less easily penetrated and rooted than sewage sludge. The difference was most clear for fresh cow dung, being less structured and having been kneaded during application, which couldn't be avoided due to its high moisture content. In that case, roots first developed around and in between the two layers of cow dung and later penetrated the cow dung itself. Addition of fertilizer P to the protective materials did not affect root growth in these materials and roots grew without noticeable damage to their tips, at least not at the studied P rate of 22 kg/ha in protected subseed placement.

With scattered placement in two holes beside the plant, the seminal roots had passed the fertilizer at a distance and thus apparently missed the volume of the soil affected by fertilizer P. Here the permanent roots and, in some instances, also branches of seminal roots, were the first to reach the fertilizer sites. Usually one or a few roots had penetrated the soil immediately surrounding the fertilizer. In a few instances, the four to five permanent roots of the first whorl had passed the fertilizer at both sides at such a distance that they also had apparently missed the affected volume of soil. In that case, the roots of the second whorl were the first to meet the fertilizer.

With deep placement, the seminal roots had usually missed the fertilizer, while some of their branches had often reached the fertilizer. The first permanent roots passed well above the fertilizer and their branches usually had not yet grown deep enough to meet the fertilizer.

The results with scattered and deep placement indicate that the retarded response, as compared to that of subseed placement (Chapter 7.3.1), resulted from the absence of roots in the part of the soil enriched with fertilizer P.

42 days after planting

At 42 days after planting, roots were found in immediate contact with single fertilizer granules or conglomerates of granules in every soil. However, at a P rate of 131 kg/ha, resulting in large conglomerates of granules at the bottom of the former plant hole, only very few roots were in immediate contact with the fertilizer.

Fertilized and non-fertilized plants had similar root distributions in the soil (Chapter 7.3.2.1). P application strongly increased the number of roots per plant (Chapter 7.3.1) and hence increased root density. Roots were not concentrated more in the soil immediately surrounding the fertilizer granules than elsewhere in the tilled layer.

Sewage sludge and cow dung were profusely rooted. However, root density in cow dung was still less than in sewage sludge. Application of fertilizer P in sewage sludge or cow dung did not affect root density in these materials.

With scattered placement in two holes beside the plant, many permanent roots had passed through and branched at the fertilizer site. With deep placement, the site of the fertilizer was less intensively rooted as the permanent roots had passed well above it. The sites were rooted mainly by branches of these roots. It was regularly observed, with scattered and deep placement, that lateral permanent roots had reached the fertilizer sites of neighbouring plants at distances of 30 and 60 cm from their base.

63 days after planting

At 63 days after planting, root distributions were similar to those at 42 days after planting, but now it was frequently observed that roots were in immediate contact with fertilizer granules, even at the high P placement rate of 131 kg/ha. Often, thin branches of roots had grown through the highly porous granular residue of the fertilizer. Also, root concentration in the soil surrounding the fertilizer granules was now no higher than elsewhere in the tilled layer.

Photograph 3. X-ray microanalysis of fertilizer granules.

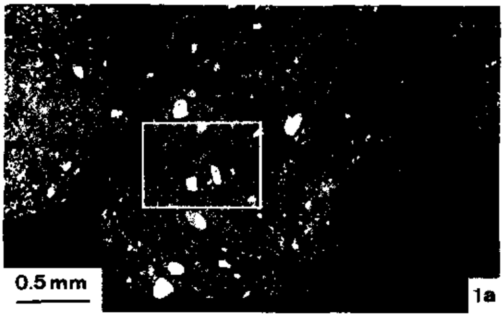
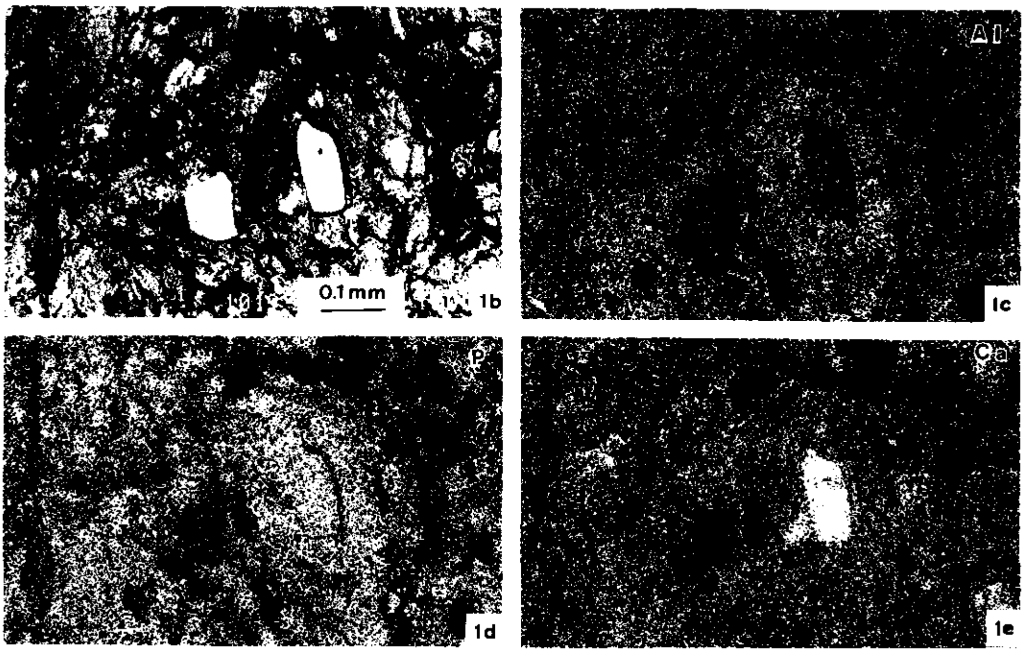


Fig. 1a. Backscattered electron image of a fresh granule.

Fig. 1b. Backscattered electron image of a central area of a fresh granule (see Fig. 1a). The bright large crystal in the center (arrow) is a titanium oxide, a rare impurity in the granules.

Fig. 1c-1e. X-ray maps of Al, P and Ca of Fig. 1b are shown in Figures 1c, 1d and 1e.



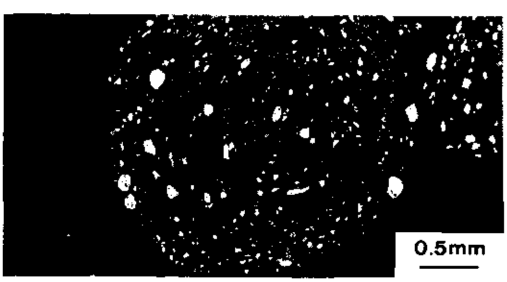


Fig. 2. Backscattered electron image of a granule incubated for 20 weeks in soil. To the right of the top of the granule a soil aggregate is present on the outside.

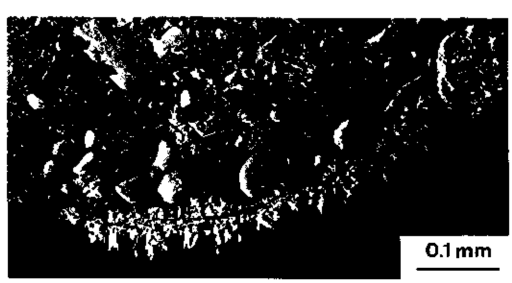


Fig. 3. Backscattered electron image of a peripheral area of a granule incubated for 3 weeks in soil.

7.4 BEHAVIOUR OF FERTILIZER P IN SOILS.

7.4.1 Compositional changes in triple superphosphate granules

Fertilizer granules were found to remain in the soil after application. After placement, residual granules were easily recovered from the application sites at the end of the trials, which was about 600 days after application, provided the sites of the fertilizer placement had not been disturbed during seedbed preparations, weedings and harvest. After broadcasting and incorporation into the soil, residual granules were observed on the soil surface until the end of the trials, notwithstanding the seedbed preparations for the second and third crop and nine weedings. They could be best observed when the soil was dry and more easily on the plots with the higher P application rates. In soil pit walls, many individual residual granules were found in the tilled layer at 600 days after application. Residual granules were found in all soils, but were more easily seen in the granite soils (15, 6) and rhyolite soil (12), because of the greater contrast in colour between the white residue and the dark reddish brown (5Y/R 3/3) soil.

Residual granules were about equal in size to fresh granules. However, they were highly porous and very friable, whereas fresh granules were firm and not porous. After application, the granules lost some of their mass, revealed in a decrease in bulk density. During the first 21 days in the soil, the mass loss was about 69 % and from 21 to 170 days about 2 %. Residual granules contained about 12 % P (mass fraction). Thus, the calculated P losses from the granule at 21 and 170 days after application were 80.7 and 81.0 % respectively (Table 15). The results indicate that a major part of the dissolution of fertilizer P and subsequent dissipation into the soil occurred within the first 21 days after application.

Table 15. Changes in density and P content of a triple superphosphate granule after application in soil. Granules were placed at a P rate of 44 kg/ha in the felsite-andesite soil (Field 2). They were measured in three replicates. Each replicate was composed of a sample of five granules.

Time after application (day)	Diameter (mm)	Volume (mm^3)	Mass (mg)	Density (mg/mm^3)	P content (mass %)	Mass loss (%)	P loss (mass %)
0	2.9	13.5	23.6	1.75	19.4		
21	3.3	18.6	10.2	0.55	12.0	68.8	80.7
170	3.1	16.3	8.4	0.52	12.5	70.5	81.0

Fresh and residual granules were studied in detail with optical microscopy, X-ray diffraction, scanning electron microscopy and X-ray microanalysis by Henstra et al. (1981). Fluorapatite ($Ca_5(PO_4)_3F$), brushite ($CaHPO_4.2H_2O$) and an amorphous phosphorus compound were detected in residual granules (Photograph 3, Figures 2 and 3). In fresh granules, monocalcium phosphate monohydrate ($Ca(H_2PO_4)_2.H_2O$) was the only crystalline P compound detected with X-ray diffraction, but with X-ray microanalysis several large crystals were identified as fluorapatite (Photograph 3 , Figure 1 a-e).

Fluorapatite was evenly distributed in sections of all granules. The crystals were up to 100 μm in size and several had hexagonal outlines. Since fluorapatite was not observed in the X-ray diffractograms of fresh granules and intense lines did appear in the diffractograms of residual granules, part of the fluorapatite was assumed to have been formed after application. Fluorapatite remained in the granules up to the termination of the trials (600 days after application). The presence of large fluorapatite crystals in fresh granules had apparently resulted from an incomplete acidulation during the manufacture of the triple superphosphate from Moroccan phosphate rock.

Brushite was formed after fertilizer application in the soil and it was concentrated mainly at the periphery of the spherical granules. The peripheral crystals were about 1 to 50 μm and were grouped together in discontinuous bands that were not wider than 100 μm (Photograph 3, Figure 3). Other lath-shaped crystals of brushite were present within the granules either in groups or alone. The amount of brushite decreased with time. At 170 days after application, the brushite diffraction lines were much weaker and the number of crystals was lower than at 21 days after application (Table 16).

*Table 16. Presence of crystalline compounds in sections of fresh and residual granules at 21 and 170 days after application in soil, cow dung or sewage sludge. (Bands), areas with new-formed lath-shaped crystals at the periphery of the granules (see Photograph 3, Figure 3). ($\Delta P/P$ * 100), estimated mean-fraction in % of the observed periphery covered with Brushite bands. (Uniaxial crystals), crystals polished perpendicular to the c-axis. (+) crystals are present, (-) crystals are absent.*

	Felsite-andesite Field 2		Rhyolite Field 12		Cow dung Field 12		Sewage sludge Field 12		Fresh
	21 day	170 day	21 day	170 day	21 day	170 day	21 day	170 day	0 day
No of granules in section	10	14	12	10	1	20	13	16	20
No of granules with bands	4	1	1	1	1	10	7	1	0
$\Delta P/P$ * 100	7.0	0.5	0.5	0	39.0	4.0	30.0	1.0	0
Uniaxial crystals	+	+	+	+	+	+	+	+	+
Large lath crystals	+	-	+	-	-	+	+	+	-
Tiny lath crystals	+	-	+	-	-	+	+	-	-

The amorphous P compound formed the matrix in which the crystals were embedded. It was composed, for the major part, of O, Al, P, Ca and Fe and, for a minor part, of F, Na, Mg, Si, S and K. The variations in peak intensities and peak ratios of these elements in the spectra of different areas in a matrix were less in sections of granules at 170 days than at 21 days after application or of sections of fresh granules. This indicates that the amorphous matrix had become more homogeneous with time. The amount of Na, Mg, S and K decreased with time and generally peaks of these elements were not observed in the matrix at 170 days after application. In some homogeneous matrix areas, only peaks of O, F, Al, P, Ca and Fe were observed at that time.

Three non-phosphate minerals were found in the X-ray diffractograms: anhydrite ($\gamma CaSO_4$), gypsum ($CaSO_4.2H_2O$) and quartz (SiO_2). Fluorite (CaF_2), which was mentioned by the manufacturer as a constituent of fresh granules (Table 4), was not detected in this study. Anhydrite and gypsum were seen as weak lines in both fresh and residual granules. Their line intensities decreased with time and they were hardly visible at 170 days after application. Quartz was present in all samples and concentrated with time as a result of residual enrichment.

Changes in composition of triple superphosphate granules were similar for different application methods and P rates and in soils, despite the variations in P-sorption capacity and climate. The data presented in Table 16 show a difference in abundance of brushite at the periphery of the residual granules. The estimated mean fraction of observed periphery covered with brushite bands was higher for protected than for non-protected residual granules. This might be an indication that formation of brushite at the fertilizer site is enhanced when the fertilizer is covered with cow dung or sewage sludge. However, the number of measurements was too small to allow a definite conclusion on the compositional changes in triple superphosphate granules in quantitative terms.

7.4.2 Transport and sorption of fertilizer P

Transport and sorption of placed fertilizer P in soil were studied using samples taken at 21, 42, 63 and 170 days after application in the absence of plants. Figure 38 shows that P had dissipated rapidly from the fertilizer granules and that a major part of the transport had occurred within 21 days after application. The fertilizer P was transported over short distances from the granules. Most of it was sorbed in the first 6 centimeters of the soil. Even at the high P rate of 131 kg/ha, no fertilizer P was found in the subsoil at a depth of 18 to 23 cm below the granules, not even on the volcanic ash soil with a low P-sorption capacity at 170 days after application. Hence, it is concluded that the placed fertilizer P was retained in the tilled layer and so remained within reach of maize roots.

The fertilizer P penetration fronts were not steep. At a P rate of 22 kg/ha and corresponding - low sorption levels P had already penetrated in the second and, to a less extent, into the third 2 cm layer of soil.
P concentration in the soil directly below the granules reached high levels of about 10,000 mg/kg. Since it strongly increased with P application rates, the maximum P-sorption capacities under field conditions had probably not yet been reached in any of the soils. Surprisingly, the P-sorption capacities under field conditions were much higher than estimated from laboratory experiments (Table 17).

Sorption of placed and of broadcast and incorporated fertilizer P in the presence of plants was measured in samples taken at the end of the trials at about 600 days after application i.e. after three growing seasons. At 25 to 30 cm below the soil surface, no or only slight differences in P concentrations in the soil were found between the fertilized and non-fertilized plots (Figure

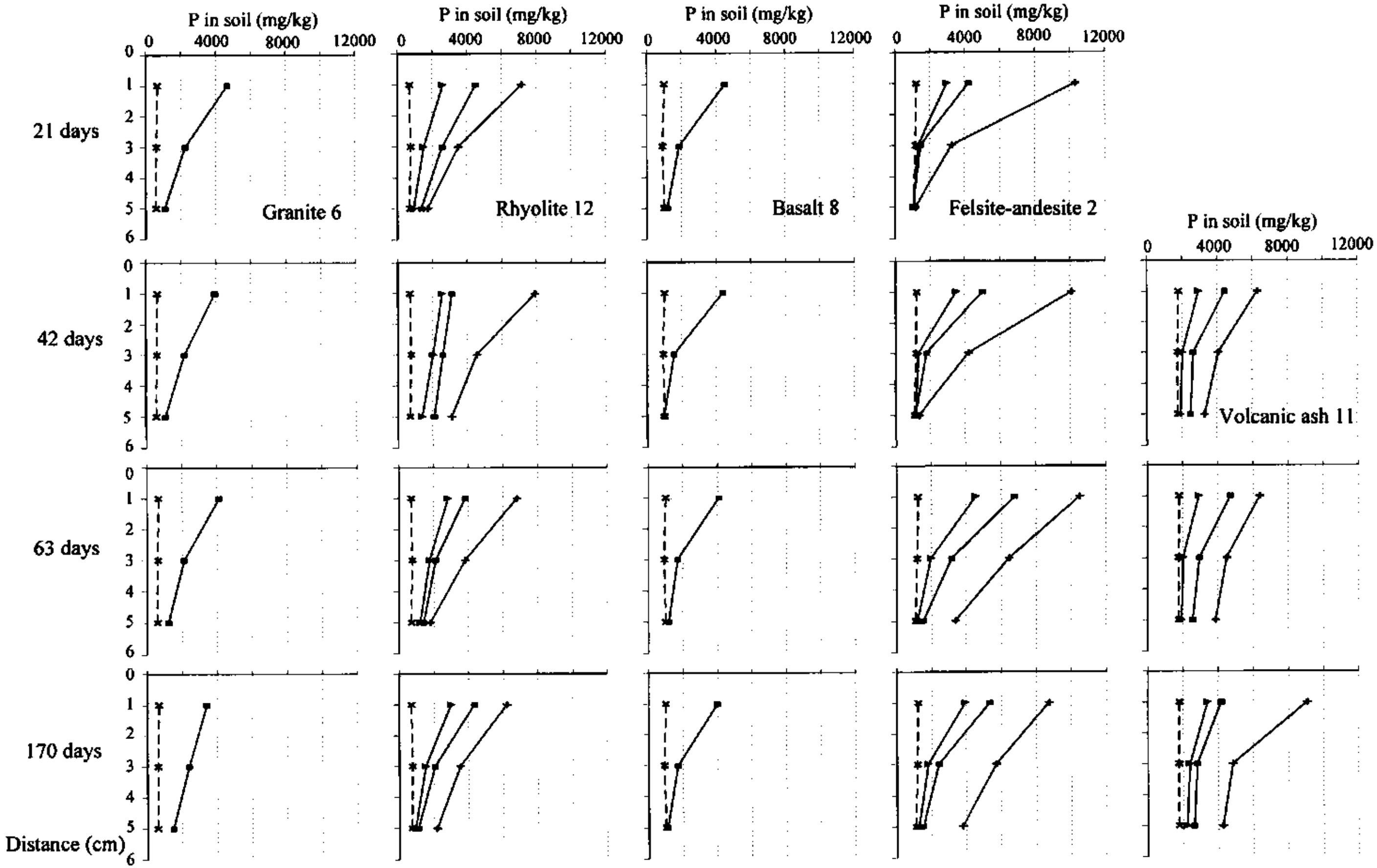


Figure 38. Total P concentration in soil in relation to the distance below placed fertilizer at 21, 42, 63 and 170 days after application in absence of plants. Treatments: no P(x); P 22(▸), 44(■) and 131(+) kg/ha.

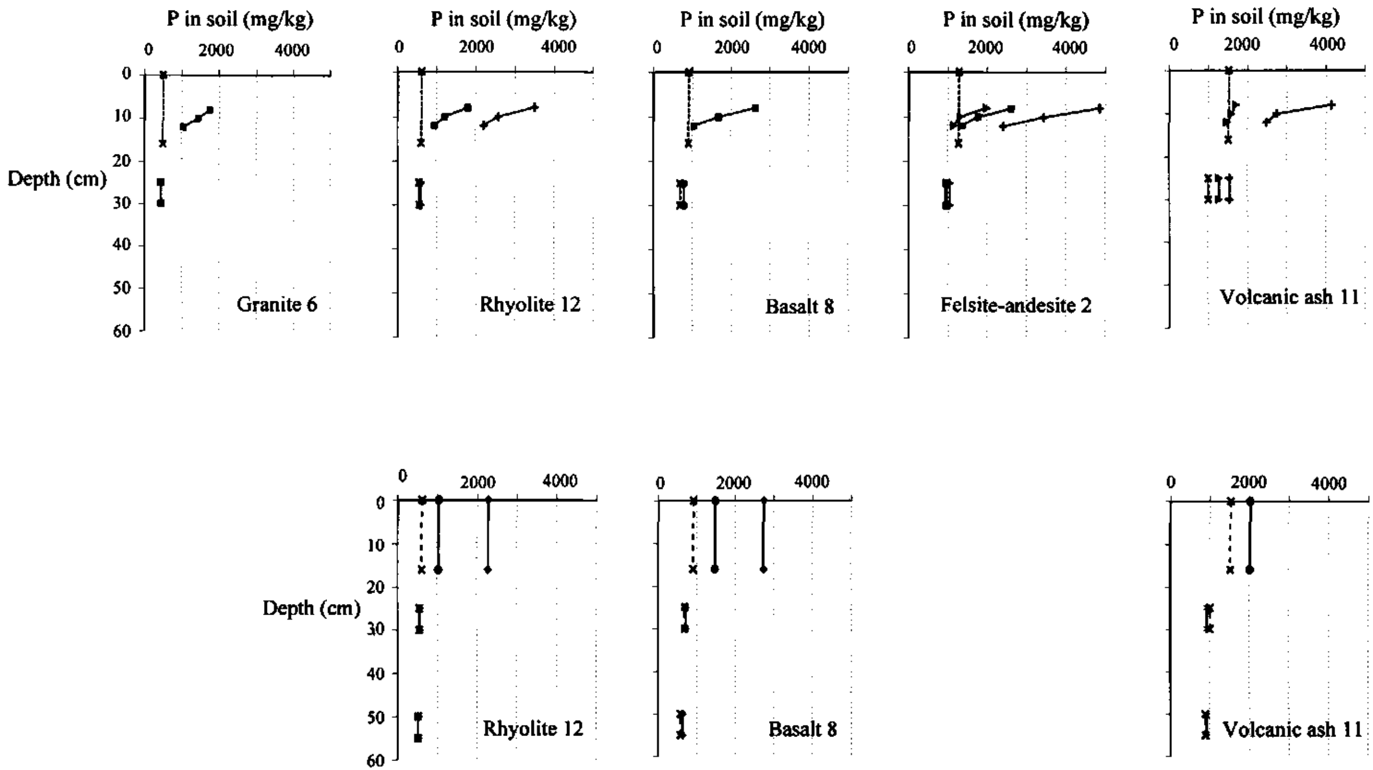


Figure 39. Total P concentration in soil in relation to the depth below the soil surface at about 600 days after P application in the presence of plants (three growing seasons). Above: subseed placement; no P(x), P 22(▲), 44(■) and 131(+) kg/ha. Below: mixing; no P(x), P 512(●), 1048(★) and 2096(◆) kg/ha.

39). When taking the spatial differences in P concentrations in the soil within a block of treatments into account, it is concluded that the fertilizer P was retained in the tilled layer even at the highest application rates and even on the low P-sorbing volcanic ash soil(11), and so remained within reach of maize roots during three growing seasons.

Sorption of protected placed fertilizer P is compared with that of unprotected placed fertilizer P in Figure 40. P concentration in soil directly below the cow dung and sewage sludge had increased less than in soil directly below unprotected fertilizer, and even less when the thickness of the protective materials (2 cm) had been taken into account. This means that cow dung and sewage sludge were suitable materials for diminishing contact between fertilizer P and soil at the rates used in the experiments (P 22 kg/ha, cow dung or sewage sludge 100 cm^3/plant).

Table 17. P contents (mg/kg) measured in three soils directly below placed fertilizer at a P rate of 131 kg/ha, and a comparison between measured P-sorption capacities (mg/kg) under field conditions and estimated P-sorption capacities from laboratory experiments (see Table 2 and Figure 9).

Soil/ Parent material	Field no	P(total) fertilized soil	P(total) native soil	P-sorption capacity (field)	P-sorption capacity (laboratory)
Felsite-andesite	2	10,492	1,167	9,325	870
Rhyolite	12	7,902	717	7,185	445
Volcanic ash	11	9,073	1,780	7,293	60

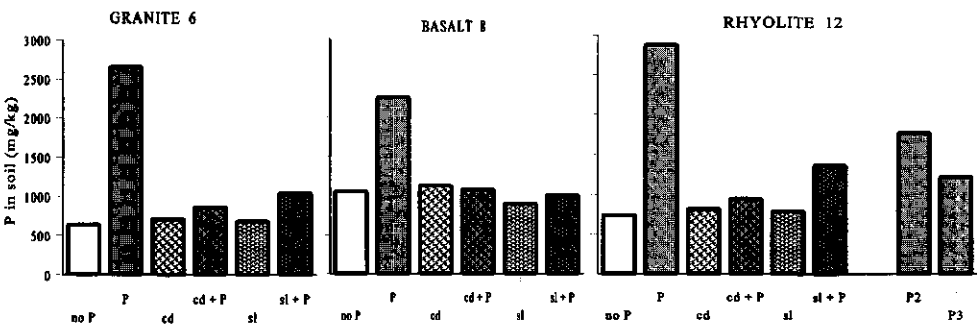


Figure 40. Total P content in the first two cm of soil either below residual P fertilizer granules (subseed placement) or below cow dung[cd] or sewage sludge[sl] (protected subseed placement) at 63 days after application. P application rate: 22 kg/ha. For the rhyolite soil also total P content is given for the second(P2) and third(P3) two cm of soil with subseed placement. (For the positions of the materials, see Figure 12).

7.4.3 Availability of fertilizer P

The increase in the P-Olsen value (ΔP-Olsen) upon P application in the soil is shown in Figure 41 as a function of the amount of fertilizer P sorbed (ΔP-total) for five soils at 21, 42, 63 and 170 days after placement in the absence of plants, and at 600 days after placement and mixing in the presence of plants. The ΔP-Olsen values increased more or less linearly with increasing ΔP total in soil in each diagram. The relationships remained more or less equal with time and were similar for the soils. This means that a more or less constant fraction of the sorbed fertilizer P was recovered in the Olsen extract irrespective of the amount sorbed, i.e. rate of application, time of application, method of application, distance below the placed fertilizer granules, the presence of plants, and soil type. At low P application rates with mixing (66 and 131 kg/ha), where only P-Olsen values were measured, the P-Olsen values in the fertilized tilled layers after three growing seasons were still higher than those in the non-fertilized layers in each soil (Table 18).

Table 18. P-Olsen values (mg/kg) in the tilled layer at about 600 days after P application for six soils. P was broadcasted and incorporated. Soil samples were taken after three maize crops, except for Field 11 where two crops had grown.

Soil/	Field no	P application rate (kg/ha)				
Parent material		0	66	131	524	2,096
Granite	15	2.9	3.7	8.0	35.4	191.8
Granite	6	2.2	3.7	6.6	37.4	151.0
Rhyolite	12	3.3	4.5	5.4	27.8	148.6
Basalt	8	3.5	4.0	5.8	37.5	171.2
Felsite-andesite	2	1.9	3.0	6.3	36.8	166.8
Volcanic ash	11	38.0	44.7	47.4	118.1	

The availability of P in residual granules, as indicated by P-Olsen, decreased rapidly during the first 21 days after application and gradually thereafter (Table 19). However, the P-Olsen values remained well above those of the soils. The presence of plants had no effect on the P availability in the residual granules. These results are in line with the findings that the compositional changes within the fertilizer granules had taken place for the major part immediately, within three weeks, after application.

Table 19. P-Olsen values in fertilizer granules as function of the incubation time. P rate was 44 kg/ha. Granules were placed in the felsite-andesite soil (2) in the absence or in the presence of plants.

Time after application (day)	Plants	P-Olsen value (mg/kg)
0		40,365
21	absent	9,000
170	absent	4,180
170	present	3,913
600	present	3,120

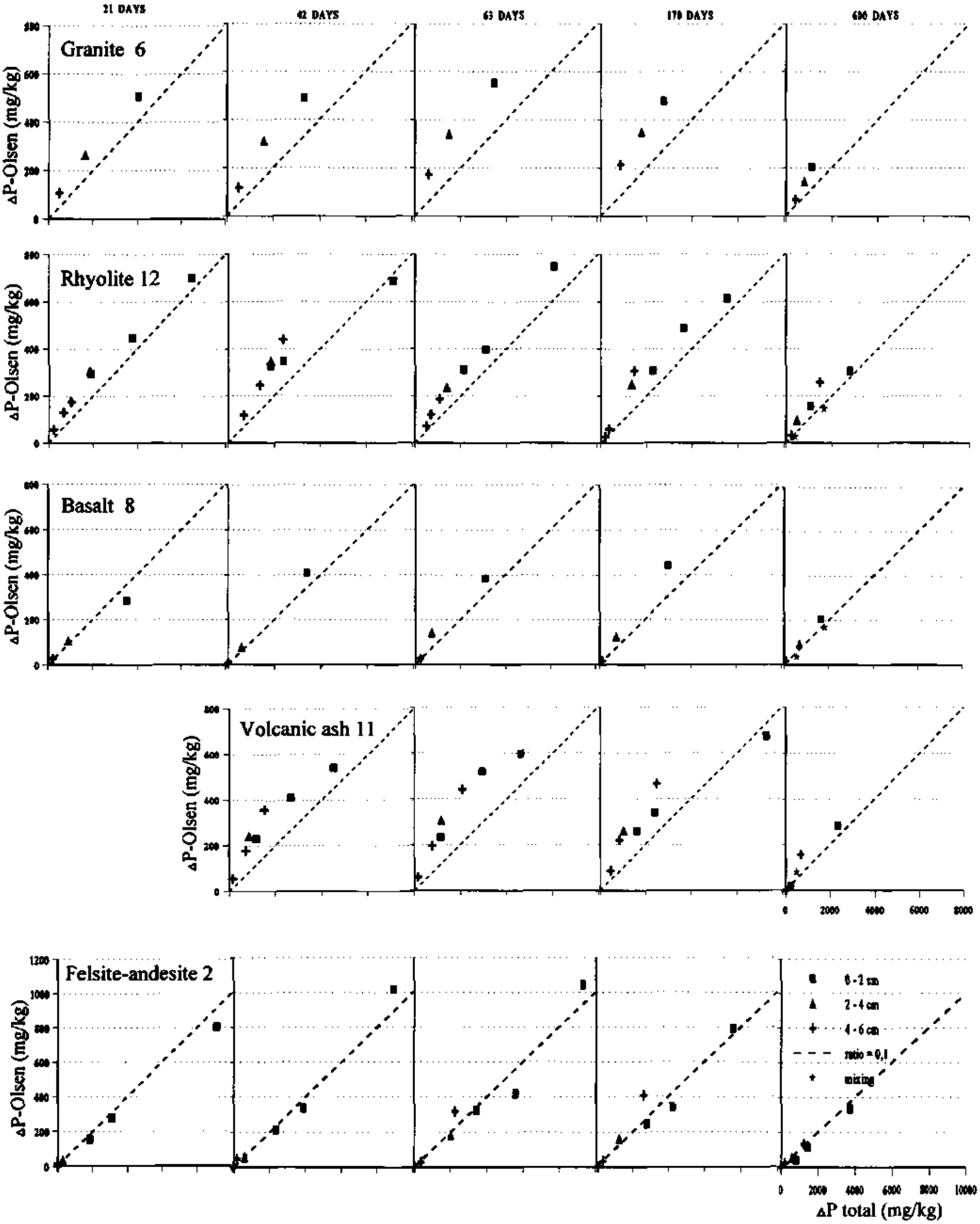


Figure 41. Relationships between ΔP-Olsen and ΔP total in soils immediately below placed fertilizer at 21, 42, 63 and 170 days after P application in the absence of plants, and at 600 days after P application in the presence of plants. P rates were: 22, 44 and 131 kg/ha. For the Fields 12, 8 and 11, the relationship was shown in soils of the tilth layer with mixing at P rates of 524 and 2,096 kg/ha at 600 days after application, as a reference.

8 GENERAL DISCUSSION

8.1 MAJOR FINDINGS

The overall aim of this study was to improve our understanding of the fertilizer phosphate - soil - maize crop interactions, to devise and test methods to increase the crop response to fertilizer P in tropical soils with low levels of available P and high P-fixation capacity and to increase the recovery and utilization of fertilizer P. An integrated study of fertilizer phosphate - soil - maize interactions involving laboratory, greenhouse and field experimentation was undertaken for that purpose. The laboratory and greenhouse experiments were used for selecting appropriate sites for field trials and to support the interpretation of the trial field results.

The major findings of the results are summarized here in relation to the objectives as specified in Chapter 5.2. They are discussed further on the basis of the interactions between fertilizer, soil and plant in the Chapters 8.2, 8.3 and 8.4.

<u>1 P status of the soils:</u>
Most of the soils in the Kisii area are low in available P and have medium to high P-sorption capacities. P-Olsen values ranged from 1.6 to 3.2 mg/kg and P-sorption capacities from 445 to 870 mg/kg for the five representative fields of the granite soils (Fields 15 and 6), rhyolite soils (Field 12), basalt soils (Field 8) and felsite-andesite soils (Field 2).
Crop production was limited by the low P status of the soils. If no P fertilizer was applied, grain yields averaged over three crops ranged from 612 to 5,647 kg/ha on these soils. Total P content of the soils appeared to be more indicative for crop yields than P-Olsen. Crop yields and P content were related to soil type and parent material. They increased in the following order: granites < rhyolite < basalt < felsite-andesite < volcanic ashes. Total P values were 490 and 549 mg/kg (granite soils); 675 mg/kg (rhyolite soil); 920 mg/kg (basalt soil), 1,035 mg/kg (felsite-andesite soil), and 1,681 mg/kg (volcanic ash soil) respectively.
An exception was formed by the soils developed in volcanic ashes. These soils were high in P-Olsen and low in P-sorption capacity, resulting in an absence of a crop response to fertilizer P and even to a luxurious P uptake in plants.

<u>2 Compositional changes of triple superphosphate and P sorption in the soils:</u>
Monocalcium phosphate, the main component of triple superphosphate, rapidly dissolved after application. Three weeks after application, the dissolution was complete as was most of the dissipation of P into the soil. Granular residues of fertilizer, in which brushite (dicalcium phosphate dihydrate), fluorapatite and an amorphous unidentified P compound were detected, remained in the soil until the end of the trials (about 600 days after application).
The fertilizer P that dissipated from the granules was sorbed in high amounts at short distances from the granules. The form in which P was sorbed could not be discovered. With increasing P application rates, both the fertilizer P content and transport distance of fertilizer P in the soil increased. Fertilizer P was sorbed to a much higher level than expected on the basis of the P-sorption studies in the laboratory.
Because of the strong sorption, downward transportation of fertilizer P was limited to the

tilled layer. Even at the highest P application rates with placement (131 kg/ha) or mixing (1,024 and 2,048 kg/ha), and even on the reference volcanic ash soil with a low P-sorption capacity, no fertilizer P was recovered at a depth of 25 to 30 cm below the soil surface at the end of the trials.

3 Efficacy of fertilizer application methods:

Application of P stimulated plant growth (including root growth), shortened the growing season and increased grain yields. Compared to the initial responses, good residual responses were found in the second and third season, even at the lower application rates, indicating that fertilizer P remained available up to at least the end of the trials. Placement of P fertilizer induced a starter-effect. The start of the plant response corresponded with the moment plant roots reached the soil in the immediate surroundings of the fertilizer site. The moment at which the starter-effect appeared became later in the following order: subseed placement and protected subseed placement > scattered placement in two or four holes beside the seeds > deep placement beside the seeds. Protected subseed placement yielded an additional effect of the protective material itself, especially if cow dung or sewage sludge were used. At overlapping P application rates i.e. 44 to 131 kg/ha (in P_2O_5: 100 to 300 kg/ha), subseed placement and mixing in the tilled layer resulted in similar yield responses. High P application rates should be discouraged as it may cause fertilizer burn with subseed placement (131 kg/ha) and it stimulated weed germination and growth with mixing (≥524 kg/ha).
The yield maxima ranged from 3,074 to 10,293 kg/ha. There was some evidence that the rootability of the subsoil and, hence, the susceptibility to drought, was a main factor limiting the yield maxima at high P application rates.

4 P utilization and recovery of fertilizer P:

When P limited grain yield, the relationship between P in above-ground plant components (y) and P in grain (x) could be described by the equation: $y = 0.46+1.13x$ and the relationship between grain yield (z) and P in above-ground plant components (y) by the equation: $z = 620(y-0.50)$. Plants should be able to take up at least about 0,5 kg P per ha to develop sufficient plant tissue for producing grains. The efficiency of P utilization (z/y) increased from about 350 to 550 kg/kg after P application, up to rates of about 44 kg/ha. With increasing rates, the efficiency of utilization gradually decreased to about 300 kg/kg at P rates above 524 kg/ha, as a result of a luxurious uptake of fertilizer P.
The cumulative apparently-recovered P fraction in plants after three crops was about 0.25 at an application rate of 22 kg/ha with subseed placement. The residual recoveries in the second and third seasons were not or slightly lower than the initial recovery in the first season. The recovery fractions were about the same for all soils and hence, did not follow the differences in P-sorption capacities. Protection by mantling the fertilizer granules in cow dung, sewage sludge or a soil rich in P had no effect on the recovery of fertilizer P.

5 P fertilizer application recommendation:

In the soils with P limiting crop production, the available P levels (P-Olsen) of native P were very low, almost near the detection limit. Since grain yields ranged from 612 to 5,647 kg/ha, the P-Olsen value should not be used, or at least not as the only parameter, for determining the P status of the Kisii soils and should not form a basis for P fertilizer application recommenda-

tion. Instead, total P and the rootability of the (sub)soil seem to be better parameters. After fertilizer P application, P Olsen values were increased in the P enriched soil volume (up to 800 mg/kg) and the ΔP Olsen values were related to the ΔP total contents. The available P fraction was about 0.10 to 0.15 and remained fairly constant with time, notwithstanding differences in soil properties, for instance in P-sorption capacities. Therefore, the P-Olsen value might be a suitable parameter for following the behaviour of fertilizer P and to form a basis for predicting (residual) grain yield responses to fertilizer P.
Determining P-sorption isotherms in the laboratory and deriving the P-sorption capacity, i.e. the Standard P Requirements, from it, does not form a suitable basis for recommending the appropriate fertilizer application rates in the field.

It is surprising that the expected rapid fixation did not occur in these high P-fixing soils and that very high P Olsen values in the P-enriched soil volume remained up to the end of the trials, about 600 days after application. Notwithstanding these high P-Olsen values, the plant recovery of fertilizer P was low. Although fertilizer P was efficiently utilized, a sufficient recovery allowing maximum grain production could only be obtained with relatively large amounts of fertilizer P. In the following sub-chapters, the results are discussed further on the basis of the interactions between fertilizer, soil and plant as given in Figure 42.

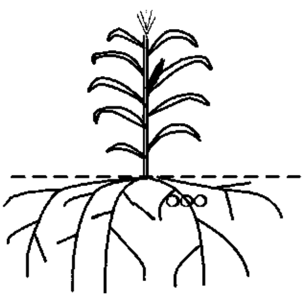


Figure 42. Fertilizer-soil-plant interactions

8.2 INTERACTIONS BETWEEN FERTILIZER P AND SOIL

8.2.1 Dissolution and dissipation of fertilizer P into the soil

Within three weeks after application, monocalcium phosphate monohydrate, the main component of triple superphosphate, had been dissolved and a granular residue composed of brushite, fluorapatite and an amorphous P compound had been formed. The rapid dissolution of monocalcium phosphate monohydrate and the formation of brushite at the fertilizer site are well-known and understood phenomena (Lawton & Vomocil, 1954; Brown & Lehr, 1959; Lindsay & Stephenson, 1959). Leenaars-Leijh (1985) found, in a laboratory experiment with soils from my trial fields, that most of the compositional changes had already occurred within the first day after application. This indicated that the plants in the trials only came into contact with transformed fertilizer P.

Steep penetration fronts of fertilizer P were to be expected from the shapes of the P-sorption curves found in the laboratory experiments (Figure 9), but were not observed in the field (Figure 38). In each soil, P sorption below the granules increased with the P application rate and decreased with depth. Decreasing P concentrations with depth were also reported by Benby and Gilkes (1987) in a laboratory experiment when large triple superphosphate grains were applied to moist soils. Spreading processes probably dominated the transport and sorption of fertilizer P in the soils. Convective dispersion in the soils with a high porosity and many inter and intra-aggregated pores may certainly have contributed to the spreading of the penetration front. Moreover, the initial high density of the monocalcium phosphate solution of about 1.3 kg/l (Lindsay and Stephenson, 1959) may have favoured the convective flow and dispersion. Furthermore, P sorption does not proceed instantaneously and, finally, the passing solute changes in chemical composition. For instance, during sorption the pH increases, while P and Ca concentrations and ionic strength decrease. This may also have contributed to the front spreading. Modelling such processes is complicated. A probabilistic approach as proposed by Van der Zee and Bolt (1990), may be helpful. They included spatial variability in their model and calculated that their approach is suitable for pulse-type input conditions. Such conditions are likely to have existed during the initial dissipation of P from the fertilizer granules and also later on in the P-enriched soil immediately surrounding the residual granules, as a result of frequent heavy rains.

8.2.2 Sorption of fertilizer P

Fertilizer P was sorbed at very high levels in the soil immediately below the fertilizer granules, when placed in plant holes at P rates of 22, 44 and 131 kg/ha. The sorption level under field conditions exceeded 4 to 40 times the sorption levels measured in the laboratory (Table 17). Furthermore, field and laboratory data were apparently unrelated. Thus, the sorption data obtained in these kinds of laboratory experiments are not suitable for predicting the P-sorption capacity and, hence, the Standard P Requirements (SPR) under field conditions when triple superphosphate is applied. Three factors can be mentioned to explain the higher P-sorption levels under field conditions. These are:

1 temporarily extreme chemical conditions during transformation of monocalcium phosphate
2 interference of calcium derived from triple superphosphate
3 incubation time

Extreme chemical conditions:
The extremely-acid and highly-concentrated solution that develops during dissolution and transformation of monocalcium phosphate, strongly reacts with the soil constituents surrounding the granules. The eventual retention of P results from adsorption or precipitation in the diffuse double layers, in Stern layers and in the bulk solution, or both processes simultaneously. Since micro-organisms probably do not survive such an acid and saline environment, microbial immobilization can be disregarded.

Under field conditions, the initial pH was much lower than in the laboratory (about 1.8 versus about 6.0) and the initial P concentration much higher (about 4,000 mmol/l versus about 1 mmol/l). Since P sorption increases with decreasing pH and with increasing P concentration (Black, 1942), the P sorption can be expected to be higher in the field than in the laboratory. Sorption of P at low pH leads to neutralization of the H^+ produced in the transformation of monocalcium phosphate according to the following reactions:

$M\text{-}OH + H^+ \longrightarrow M\text{-}OH_2^+$ and $M\text{-}OH_2^+ + H_2PO_4^- \longrightarrow M\text{-}H_2PO_4 + H_2O$.

With respect to precipitation, favourable field conditions may have existed as well. It is likely that the highly-acid solution dissolved part of the soil minerals such as kaolinite and goethite. Dissolution of these minerals leads to neutralization of the H^+ produced and to precipitation of iron and aluminium phosphates, and so contributes to the high values of total P. The neutralization of H^+ was found to occur within 3 weeks and was complete even in the soil immediately below the fertilizer when it was placed at a P rate of 131 kg/ha.

If all iron and aluminum present in the soil was to be used to form precipitates of strengite and variscite, then maximum P contents in the soils would range from 86,800 to 170,500 mg/kg. However, the highest level found in the trials was 9,440 mg/kg. Thus, only a minor fraction of the soil Fe and Al may have been involved in the assumed precipitation. In this study, no evidence of Fe- and Al phosphate precipitates was found. The X-ray diffractograms of soil material that had been in immediate contact with fertilizer granules, placed at a P rate of 131 kg/ha, were not different from those of non-affected soil material, which implies that crystalline P compounds were absent or present in too low amounts to be detected. In a few X-ray microanalyses of soil particles attached to residual granules, no concentrations of P and Al or P and Fe were found.

When comparing these results with those found in the literature, it is clear that results from laboratory experiments are different from those of this field study.
Lindsay & Stephenson (1959) added small amounts of soil to a highly-concentrated solution of monocalcium phosphate monohydrate. They found crystalline Fe and Al phosphates with a complex composition and dicalcium phosphate, together with colloidal amorphous solids that could not be identified. Martin et al. (1988) studied P sorption on goethite surfaces and identified a crystalline phosphate $Fe_3Mn_2(PO_4)_{2.5}(OH)_2$ (griphite). However, they used solutions of KH_2PO_4. Willet et al. (1988) studied P sorption on ferrihydrate particles. They found a concentration of P on the surfaces of the particles followed by a migration into the particles, but they used synthetic porous ferrihydrate and solutions of NaH_2PO_4.

<u>Interference with calcium derived from triple superphosphate:</u>
The solution that dissipates from the triple superphosphate granules contains calcium at a concentration of about 1,400 mmol/l (Lindsay & Stephenson, 1959). In the present study, calcium derived from the fertilizer was sorbed in the immediately surrounding soil (Table 20).

Table 20. Ca sorption (mmol/kg), P sorption (mmol/kg) and Ca/P sorption ratio in two soils directly below fertilizer granules placed at a P rate of 131 kg/ha at 21 and 170 days after application.

Soil/	Field	Ca sorption		P sorption		Ca/P	
Parent Material	no	21 days	170 days	21 days	170 days	21 days	170 days
Felsite-andesite	2	148	115	311	278	0.48	0.41
Rhyolite	12	95	80	220	178	0.43	0.45

The Ca contents varied slightly with time and soil type, similarly to the P contents. Hence, if expressed in a Ca/P molar ratio, the slight variation in time and soil type disappeared. This leads to the hypothesis that Ca and P sorptions were related, either in precipitation or adsorption. Ca and P could have formed precipitates. If brushite had been formed in the surrounding soil, and taking into account the fact that part of the Ca is retained in the residual granules, then it can be calculated that about 45 % of the dissipated P would have been retained. Hence, other P compounds should have been formed as well. If more basic calcium phosphates had been formed, then a lower P fraction would have been retained. If Ca had formed double phosphates with soil components such as Al, Fe, Mg, K, Na, or HCO_3^-, as mentioned by Kostov (1968), then a higher P fraction would have been retained. In a laboratory experiment, Davey and Shayan (1980) found a number of crystalline and amorphous products within the reaction zone up to about 3 mm from triple superphosphate pellets placed on a moist chrumic luvisol (red podzolic soil). The composition of most of these materials was dominated by Ca and P, together with smaller amounts of Fe, Al and Si and, occasionally, K. In my study, a few soil samples were examined in X-Ray diffraction, X-ray microanalysis and optical microscopy, but no evidence for the formation of calcium phosphates or calcium double phosphates was found.

Calcium present as exchangeable ions in diffuse double layers of soil constituents or in the form of exposed ions on surfaces of calcium compounds may contribute to the sorption of P (Chapter 3.5.2.). Part of the sorbed fertilizer Ca was exchangeable with ammonium acetate (Table 21). This exchangeable Ca could have contributed to the sorption of fertilizer P. Contribution of exposed Ca ions on calcium compounds in P sorption such as: $CaCO_3$, (as observed by Salingar and Kochva (1994)), $CaSO_4$, CaF_2 and Ca-silicates probably did not occur or was of minor importance, as these compounds were not found in X-ray diffraction of soil material surrounding the residual fertilizer granules.

Table 21. Comparison between exchangeable Ca in native soil and fertilized soil directly below triple superphosphate granules placed at a P rate of 44 kg/ha.

Soil/ Parent material	Field no	Exchangeable Ca (mmol/kg)		
		Native soil	P-fertilized soil 21 days	170 days
Granite	6	17	55	44
Rhyolite	12	28	60	54
Basalt	8	43	77	80
Felsite-andesite	2	54	81	85
Volcanic ash	11	79	105*	92

(*) 42 days

Incubation time:

Since P sorption increases with time, more P can be expected to be sorbed in the soils under field conditions (incubation time 21 to 560 days) than in the laboratory experiments (incubation time 5 days).

Van Riemsdijk (1979) has described the relation between P sorption and incubation time at constant P concentration and pH in soil solutions for a sandy soil containing aluminum and iron oxides and hydroxides with the equation: $S = k_1\sqrt{t} + k_2$,
where S is P sorption (mmol/kg), t is incubation time (hours), and k_1 and k_2 are constants. The constant values at P concentrations ranging from 0.09 to 8.86 mmol/l were: $0.3<k_1<1.0$ and $3<k_2<12$. According to this equation and these k values, the P sorption after 3 weeks of incubation in the field should be a factor 1.5 to 1.7 higher than after 5 days of incubation in the laboratory. Black (1942) varied the incubation time, P concentration and pH, in sorption experiments with a kaolinitic clay containing iron oxide. Making use of his results, P sorption after 30 days of incubation was calculated to be a factor 1.1 to 1.7 higher than after 2 days, when the initial P concentration varied from 0.03 to 3.23 mmol/l and final pH in solution from 4 to 6. When comparing the results of Van Riemsdijk and Black with those obtained in my study, it can be concluded that incubation time is of minor importance in explaining the large P-sorption differences between field and laboratory.

Summarising, the temporarily extreme chemical conditions during transformation of mono-calcium phosphate and the interference of calcium originating from the triple superphosphate played a major role in the sorption of fertilizer P in the soils and explains the much higher sorption levels under field conditions than in the laboratory experiments with solutions of KH_2PO_4.

8.2.3 Release and transport of fertilizer P.

Fertilizer P was found to be retained in the tilled layer of the soils and to remain well available to plants. Even after three successive growing seasons, residual granules containing brushite were recovered and high P contents in the soil immediately below the residual granules were found. Obviously, high levels of available P coincided with slow compositional changes in the residual granules and slow further transport of fertilizer P previously sorbed in the soil.

Under field conditions, soils are alternately dry and wet. Upon (re)wetting the soil, part of the sorbed fertilizer P will go into solution. Which P concentration will result under field conditions may be indicated by the determination of available P in the laboratory. In water (Sissingh's extract) and sodium carbonate (Olsen's extract), high levels of extractable P were found in soil below the placed fertilizer. For instance, in the felsite andesite soil (Field 2), the Pw and P-Olsen values in the first two cm of soil below the placed fertilizer were 256 and 425 mg/kg respectively 63 days after P application at rate of 44 kg/ha (Table 22). The corresponding P concentrations in the extracts were 128 and 685 μmol/l. They were probably below equilibrium concentrations, as soil/solution ratio is small and reaction time short in these extractions. Nevertheless, these concentrations are well above the concentration at which P uptake is assumed to proceed at a maximum rate (C max = 50 μmol/l). This implies that part of the sorbed fertilizer P was readily available for plants, even to excess.

Table 22. P-Olsen values (mg/kg) and Pw-values (mg/kg) in soil below placed fertilizer at a P rate of 44 kg/ha and 63 days after application, and corresponding P concentrations (μmol/l) in the soil extracts for the felsite-andesite soil (Field 2).

Depth (cm)	P Olsen soil	P Olsen extract	Pw soil	Pw extract
0-2 cm	425	685	256	128
2-4 cm	189	304	40	20

Rainwater percolating through the soil may carry fertilizer P downwards. Under the prevailing conditions of high annual rainfall and frequent heavy showers, well-drained soils and high soil temperature, a rapid release and subsequent relatively fast transport of fertilizer P is to be expected. Therefore, it is surprising that the fertilizer P remained highly available at the application site and that, after three successive growing seasons, no fertilizer P was recovered below the tilled layer at 25 to 30 cm below the soil surface, not even with mixing at a P rate of 2,096 kg/ha or with subseed placement at a P rate of 131 kg/ha, and not even on the low P-sorbing volcanic-ash soil (Field 11).

Soil structure probably is a relevant factor in leaching of fertilizer P. The soils had a moderate to strongly developed structure with very fine to fine subangular blocky and granular aggregates. Their porosity was high due to many inter and intra-aggregated pores. Under the usual moisture conditions, the major fraction of the pores were filled with air (Table 2). Due to such a structure and porosity, rainwater percolates very rapidly through the soil and the inter-aggregated pores soon become refilled with air, so that further mass flow, and also diffusion, is hindered. When one also considers the fact that dissolution and desorption do not proceed instantaneously, transport of fertilizer P by mass flow could well have been relatively small. In addition, individual fertilizer granules may interfere in the P dissolution when they occur at short distances from each other in a soil (Kirk & Nye, 1986). Placement of several granules together, as was done in my trials, then reduces the dissolution and subsequent transport of P in the soil more than mixing of individual granules in the tilth.

Brushite was found to remain in the residual fertilizer granules and their periphery. To comprehend these phenomena, the chemical and physical conditions at the site of the fertilizer residue are considered. Suppose a residual granule is alternately moistened and dried as a result of alternating wet and dry periods. The chemical composition of the soil solution that develops can then be calculated on the basis of the chemical reactions and equilibrium constants given in Appendix 9, assuming a congruent dissolution and maintenance of electroneutrality. Table 23 shows the results of the calculations.

If brushite is the only compound present and the atmospheric CO_2 pressure is 30 Pa, then a P concentration of $10^{-3.05}$ mol/l develops. If goethite and kaolinite, being major minerals in most of the Kisii soils and, gibbsite, another common mineral in well-drained tropical soils, are present in a brushite system, the soil solution was undersaturated with respect to the formation of strengite and variscite. In these calculations, adsorption of P on these minerals was disregarded, because adsorption data were not available for such a situation with very high P contents in the soil as a result of previous adsorption and precipitation. In this case, adsorption may be of minor importance, due to the high P contents.

A brushite system ($CaHPO_4.2H_20$) is oversaturated with respect to the formation of hydroxy-apatite, $Ca_5(PO_4)_3OH$ and octocalcium phosphate, $Ca_4H(PO_4)_3.3H_20$, while it is saturated for tricalcium phosphate $Ca_3(PO_4)_2$, and undersaturated for calcium carbonate. As a consequence, transformation of brushite into more basic and less soluble calcium phosphates is possible. During transformation, however, H^+ is produced, which lowers the pH and increases the HPO_4^{2-} concentration and so counteracts the transformation. Since transformation of brushite and of more basic calcium phosphate into strengite or variscite is unlikely to occur, brushite and fluorapatite form fairly stable minerals in soils under field conditions.
As long as brushite exists in the granular residue, the P concentration in the soil solution at the site of the residue is maintained at $10^{-3.05}$ mol/l while, as soon as fluorapatite becomes the only remaining P compound, it is calculated to be maintained at $10^{-4.76}$ mol/l. According to the P uptake - P concentration relationship as found by Barber (1979), uptake in plants from the site of the fertilizer may then proceed at a maximum rate as long as brushite is present and at a rate below the maximum as soon as fluorapatite remains as the only P source in the residue.

Table 23. Composition of solutions assuming congruent dissolution. $P.CO_2$ = 30 Pa. Concentrations in log(mol/l). Chemical reactions see Appendix 9.

System	P conc.	Ca conc.	Fe conc.	Al conc.	pH	ionic strength
Brushite	-3.05	-3.05			7.60	-2.60
Goethite			-14.50		5.66	-5.70
Gibbsite				- 8.06	5.67	-5.66
Kaolinite				-12.43	5.66	-5.70
Brushite-Goethite	-3.05	-3.05	-15.54		7.60	-2.60
Brushite-Gibbsite	-3.05	-3.05		- 7.75	7.60	-2.60
Brushite-Kaolinite	-3.05	-3.05		-12.13	7.60	-2.60
Fluorapatite	-4.76	-4.54			6.81	-4.09

At the end of the trials, after three growing seasons and about 600 days after application, the properties of fertilizer P still differed strongly from those of native P with respect to P Olsen/P total ratio. In the fertilized soil the ratio was about 0.1, whereas in the non-fertilized soil it was about 0.003. It seems reasonable to assume that in the long run fertilizer P will be distributed over the various P forms like native soil P. Soil animal activity and soil tillage will homogenize the soil and, by slow physical and chemical diffusion-precipitation processes, the fertilizer P will become more strongly sorbed and incorporated into the matrix of the soil. Thus, eventually, fertilizer P will contribute to the P uptake of the plant as though it was native soil P. The trials were too short to verify this and to verify whether the rate of the fixation process differed between placed and mixed fertilizer and among the soils. However, it is important for agricultural practice on these tropical soils to know that strong residual responses last for at least three growing seasons. Hence, application of fertilizer P is not a risky factor in farm management, because neither severe P fixation in the soil nor significant P leaching from the tilled layer are to be expected.

Summarising, dissolution, dissipation and sorption of the fertilizer P were dominated by the intrinsic properties of triple superphosphate, rather than by the chemical properties of the soils. Suggested explanations for the phenomenon that the initial rapid reactions were followed by a slow further transport and an apparently slow fixation of fertilizer P were the high porosity of the friable fine-structured soils so that, in spite of the frequent showers, pores were often air-filled and the fact that transformation of brushite and fluorapatite into strengite and variscite is unlikely to occur.

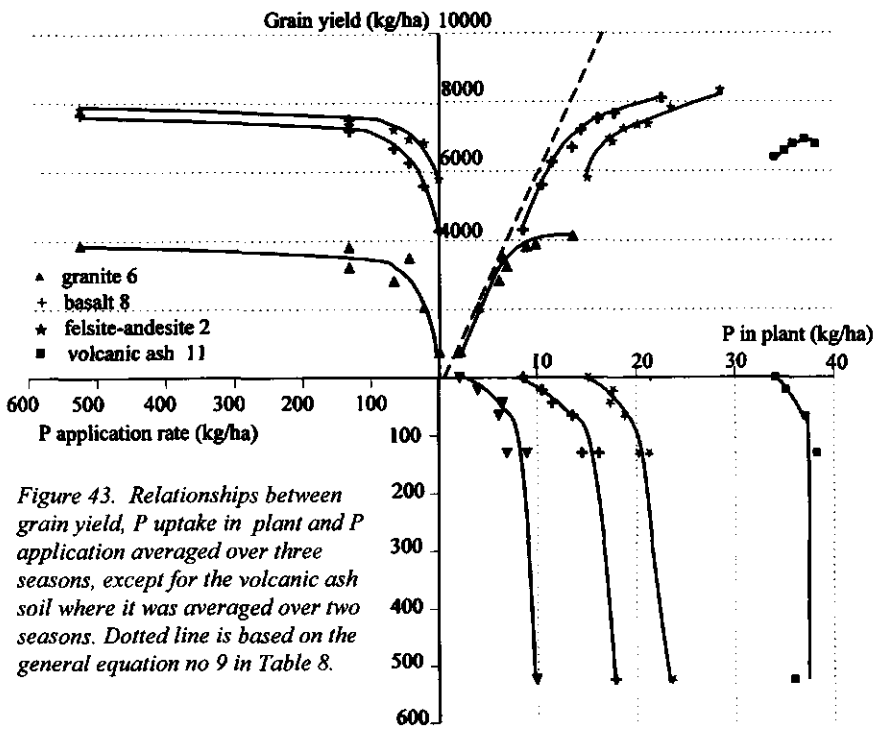


Figure 43. Relationships between grain yield, P uptake in plant and P application averaged over three seasons, except for the volcanic ash soil where it was averaged over two seasons. Dotted line is based on the general equation no 9 in Table 8.

8.3 PLANT INTERACTIONS WITH SOIL AND FERTILIZER

8.3.1 General interactions

Plants may utilize native soil P or fertilizer P. The availability of native soil P varied among the soils due to variations in total P and available P fractions. In addition, differences among the soils existed in the rootability of the subsoils. Especially on the granite soils the rootability was reduced. Here, root penetration was mostly only possible via biopores, which were irregularly distributed within the fields. As a result, the possibility of exploiting native P differed among the soils and even within a field on a soil with a less rootable subsoil.

Application of fertilizer P strongly stimulated root development. More and thicker roots developed. Hence, the soil was more intensively exploited for native P. Whether this resulted in a priming effect and, thus, to an overestimation of the amounts of fertilizer P recovered in the plant, or not or even to a negative priming effect, due to a sufficient redistribution of fertilizer P within the plant, remains a matter of speculation. Within the scope of this study, it was not a subject of investigation

The availability of fertilizer P hardly varied among soils. Figure 43 shows the relationships between grain yield, total P uptake and fertilizer application integrated over three growing seasons. For obtaining high grain yields, for instance 10,000 kg/ha, at least about 17 kg of P per ha should be taken up by maize plants.
One may wonder why such grain yields were not obtained at the P application rates of 22 to 131 kg/ha. Fertilizer was not lost from the tilled layer and the P-Olsen value in P-enriched soil remained high over three successive growing seasons, up to about 1,000 mg/kg immediately below placed fertilizer. Plant roots were present at the fertilizer site throughout, or almost throughout, the entire growing season. Although temporary droughts occurred, moisture was not a limiting factor for P uptake as luxurious P consumption occurred at high application rates. Hence, it is suggested that the capacity of the roots at the fertilizer site to absorb fertilizer P is the limiting factor for P uptake and subsequent grain production. For a more detailed picture of this subject, some calculations are made for mixing and placement of fertilizer P respectively.

8.3.2 Interaction with mixed triple superphosphate

Mixing of triple superphosphate into the soil can be considered as placement of single granules throughout the tilled layer. Suppose the fertilizer P that dissipates from a granule is sorbed in the soil at a level of 5,000 mg/kg. Then, each granule enriches a soil volume (including the residual granule) of 0,76 cm^3. {soil bulk density: 1 g/cm^3; mass of a fresh granule 23.6 mg; P content 19.4 %; P dissipation from a granule 81 % (Table 15)}. At the P application rates used and the chosen incorporation depth of 16 cm, the respective P-enriched soil volume fractions were: 0.007, 0.014, 0.027, 0.054, 0.108 and 0.216. Apparently, in the case of mixing, even at a high rate, only a minor fraction of the roots in the tilled layer comes into contact with fertilizer P. It also indicates that the chance of seminal roots and the first permanent roots making contact with the incorporated fertilizer is low. This may explain the absence of an early crop response with mixing at common application rates and the presence of a starter-effect with placement. In subtrials on these soils, De Koning (1982) and Slofstra (1984) found a strongly retarded response in plant growth to mixing of triple superphosphate at a P rate of 22 kg/ha. Although the eventual initial grain yield response was marked, it was 8 to 42 % lower than with subseed placement at the same rate (Table 24). At very low application rates, the chance that roots will come into contact with the fertilizer P becomes so low that hardly any response may develop. This is especially so if, due to a very low native P availability, plant development and that of the roots in particular, is poor. This was the case for instance on the granite soils. In such a situation, it is possible that an S-shaped response curve as mentioned by Kafkafi & Putter (1965) will develop with mixing when low application rates are included in the trials.

Table 24. Grain yield and grain yield response (kg/ha) to mixing and subseed placement of P at a low application rate of 22 kg/ha. Trails were carried out in the third season by Slofstra J.G. (1984) and De Koning J. (1982).

Soil/ Parent material	Field no	Yield Non-P	Yield Mixing	Yield Placement	Response mixing	Response placement
Granite	15	920	3,214	3,659	2,294	2,739
Granite	6	861	2,509	3,716	1,648	2,855
Rhyolite	12	1,346	3,476	3,655	2,130	2,309
Basalt	8	3,753	5,639	6,294	1,886	2,541

8.3.3 Interaction with placed triple superphosphate

Placement of triple superphosphate granules creates a limited volume of soil strongly enriched with fertilizer P near the plant base. Suppose fertilizer P had dissipated into the soil from a circular plane with a diameter of 5 cm to a depth of 4 cm and sidewards and upwards transport was limited to 0.5 cm, then a P-enriched volume is calculated of 127 cm^3 per plant. From this volume, plants should take up the fertilizer P. Suppose plant roots absorb P from this volume at their maximum rate, I max: 0.4 pmol/cm.sec (Barber 1979). Suppose a grain yield of 10,000 kg/ha requires a P amount of 16.63 kg (general equation Table 8). Suppose, further, that 20 % is derived from native P and 80 % from fertilizer P, and that 80 % of the total P uptake in plants is absorbed within 100 days. This yields a P uptake rate of 700 pmol/sec. It is then calculated that 1,750 cm of root should have been permanently present and continuously functioning at their full capacity in 127 cm^3 of soil (14 cm/cm^3). Although root length densities were not measured, such a high density was not observed in the trials. Lower root length densities are usually referred to in the literature. De Willigen & Van Noordwijk (1987) mentioned an average root length density of 3 cm/cm^3 for the tilled layer and Schröder et al.(1996) found root length densities ranging from about 1 cm/cm^3, at a distance from the plant in the tilled layer, to about 6 cm/cm^3 close to the plant base. Therefore, it is concluded that in the soils in my study, the number of roots, i.e. root surface area, present at the P-enriched soil volume was the limiting factor in fertilizer P uptake. This suggests that the availability of fertilizer P is dominated by plant root characteristics and not by soil and fertilizer properties. More attention should be paid to the significance of active root surface area in future research on tropical soils with low native P availabilities and high P-sorption capacities. Most of the research has been focused on the other aspects of P fertilizer behaviour in soils and P uptake such as: P depletion in the rhizosphere, P diffusion towards the roots and the subsequent desorption from the different sources of native soil P and dissolution of fertilizer P, especially of phosphate rock, and the factors affecting these processes such as: soil moisture, P sorption, pH, spatial distribution of fertilizer P (Van Noordwijk & De Willigen, 1979; Kirk and Nye, 1986; De Willigen and Van Noordwijk, 1987; Bhadoria et al., 1991; Gahoonia et al., 1994).

8.3.4 Interactions with triple superphosphate application methods

The calculations in Chapter 8.3.2 and 8.3.3 clearly show the importance of a sufficiently large soil volume enriched with fertilizer within reach of the plant roots. Since root distribution was found not to be affected by fertilizer application, the required fertilizer P uptake can only be obtained by creating a sufficiently large soil volume enriched with fertilizer within reach of the plant roots. A large P-enriched volume can be obtained at a high P application rate. This explains the yield increase at increasing P application rates with mixing as well as subseed placement. In the case of mixing, however, the P-enriched soil is only partly within easy reach for the roots. Furthermore, mixing high amounts of P fertilizer is discouraged because it results in a luxurious P consumption and it was found to induce strong weed growth which is a burden to farmers, especially in small-scale farming systems where weeding is mostly done manually. On the other hand, high subseed placement rates are discouraged because of interference between the fertilizer granules leading to unnecessarily high P-sorption levels (up to 10,000 mg/kg) in the soil immediately below the granules and, so, to a less than proportional enlargement of the P-enriched soil volume. The gradually developing non-linear shape in the response curve with subseed placement in the range of 11 to 131 kg/ha can probably be explained by this interference. High subseed placement should also be discouraged because of fertilizer burn to the seedling roots.

Scattered placement at planting beside the plant doesn't have the disadvantage of seedling damage and dividing the fertilizer over several holes reduces interference between fertilizer granules resulting in a larger P enriched soil volume. At the rate used in the trials (P 22 kg/ha), scattered placement in two or four holes beside the plants resulted in similar grain yields as when placed together in the plant hole. However, at this rate, conglomeration of fertilizer granules in the plant hole did not occur, so the rate was apparently too low to express the interference phenomenon. A disadvantage of scattered placement is the fact that it is rather laborious and not common in agricultural practice in South West Kenya.
Deep placement beside the plants in two holes shares the advantages of (shallow) scattered placement. However, contact between plant roots and the fertilizer is delayed and placement is even more laborious. Therefore, scattered and deep placement are not viable options.

In the case of repeated subseed placement, plants benefit from the starter-effect of freshly-applied fertilizer and the residual effects of fertilizer applied to previous crops. When more P

Table 25. Grain yield and grain yield response (kg/ha) to the protective materials cow dung and sewage sludge. Application rate 100 cm^3/plant. Fertilizer P was absent.

Soil/ Parent material	Field no	Control	Cow dung	Sewage sludge	Response cow dung	Response sewage sludge
Granite	15	1,071	3,685		2,614	
Granite	6	1,599	3,080	3,697	1,481	2,098
Rhyolite	12	2,350	4,477	4,831	2,127	2,481
Basalt	8	4,448	7,571	6,954	3,123	2,506

Table 26. Quantities of protective materials applied per plant hole and per ha, mass fractions of total P and P-water in protective materials and native soils, and quantities of total P applied with protective materials.

Field no	Type of material	Application rate (g/plant)	Application rate (kg/ha)	Mass fraction (mg/kg) total P	Mass fraction (mg/kg) P-water	Applied P (kg/ha)
15	Cow dung	48.7	2,706	1,953	80	5.2
6	Cow dung	41.3	2,294	1,860	57	4.2
12	Cow dung	64.1	3,561	3,906	341	13.9
8	Cow dung	41.9	2,328	3,720	308	8.6
	Sewage sludge	38.3	2,125	9,703	81	20.6
	'Rowo' soil	74.1	4,118	15,531	7	64.0
15	Granite soil			490	1.4	
6	Granite soil			549	2.0	
12	Rhyolite soil			675	1.9	
8	Basalt soil			920	1.6	

Table 27. Grain yields (kg/ha) with subseed placement of cow dung in the absence of fertilizer P. Trials were carried out in the first season by Oenema (1980).

Soil/ Parent material	Field no	Cow dung rate (cm^3/plant) 0	100	200	300
Granite	15	302	1,470	3,306	3,640
Granite	6	1,009	1,972	2,127	3,377
Basalt	8	4,136	6,752	6,842	8,473

is applied for each crop than the plant requires, the P availability of the soil is gradually increased. Since placement of plant seeds and fertilizer is a common practice in the small-scale farming system, repeated subseed placement fits in with the system and the low-input strategy and is, therefore, recommended. For maize, P application rates of about 20 to 40 kg/ha are advised.

Protected subseed placement introduced the phenomenon of a strong grain yield response to the protective materials themselves, especially to sewage sludge and cow dung. An amount of 100 cm^3 per plant resulted in a substantial increase in grain yields (Table 25). Since P was the main yield-limiting factor, the response should have resulted from an increased P uptake in the presence of protective materials. Since root distribution was hardly affected by the protective materials, the availability of P in the protective materials should have been higher than the P availability in the native soils. This increased availability could be related to both total P and available P in the protective materials, which were higher than in the soils (Table 26). The weak performance of Rowo soil was caused by the rather low available P level. Although total P was very high (15,530 mg/kg), the available P level was lower in the Rowo soil than in the volcanic ash soil (Field 11).
Since P was still the yield limiting factor when protective materials were applied at a volume of 100 cm^3 per plant, a further yield increase could be expected with increasing amounts of protective materials. Oenema (1980) indeed found a strong response with cow dung applied at rates up to 300 cm^3 per plant in subtrials on the granite soils (Fields 15 and 6) and on the basalt soil (Field 8) (Table 27).

8.3.5 Interactions between triple superphosphate and protective materials

Since root distribution was not affected by the fertilizer P in the protective materials and most of the fertilizer P was retained within the protective materials, the response to the protected fertilizer P suggests that P from the protective materials was absorbed at a rate below I-max (0.4 pmol/cm.sec). Increasing the fertilizer P application rate should then create a larger volume within the protective material enriched with highly available fertilizer P and, hence, should result in higher grain yields as long as P is yield-limiting. This is supported by the results of Oenema (1980). He found a strong yield increase with increasing P application rates from 5.5 to 44 kg/ha when P was mantled in a volume of 100 cm^3 cow dung per plant (Table 28).

Table 28. Grain yields (kg/ha) with protected subseed placement in cow dung. Application volume of cow dung was 100 cm^3/plant. Trials were carried out in the first season by Oenema (1980).

Soil/ Parent material	Field no	P application rate (kg/ha) 0	5.5	11	22	44
Granite	15	1,470	3,090	3,342	3,128	4,063
Granite	6	1,972	2,690	2,824	4,183	4,596
Basalt	8	6,752	7,608	6,759	8,103	9,349

The response to fertilizer P in combination with protective materials (protected subseed placement) deserves a theoretical discussion.

A positive interaction would be found if the proposed fixation of fertilizer P in the soils was prevented by the protective materials. However, since fertilizer P remained relatively well available, also without protection, such a positive interaction probably did not occur. Since most of the fertilizer was retained within the protective material and root distribution was not affected by the fertilizer, the roots within the protective materials share two P sources, viz protective material P and fertilizer P. This suggests that responses to the protective materials and fertilizer P in combined application should show a negative interaction. A negative interaction could be also expected if only part of the protective materials was enriched with fertilizer. This could have occurred, since the mainly downward-moving fertilizer P had probably not reached all the protective material above the fertilizer granules (Figure 12) and, apparently at low rates, not even all the material below the fertilizer granules. For instance, no fertilizer P was recovered below cow dung and hardly any below sewage sludge when P was applied at a rate of 22 kg/ha (Figure 40). Indeed, a slight negative interaction was found (Figure 44).

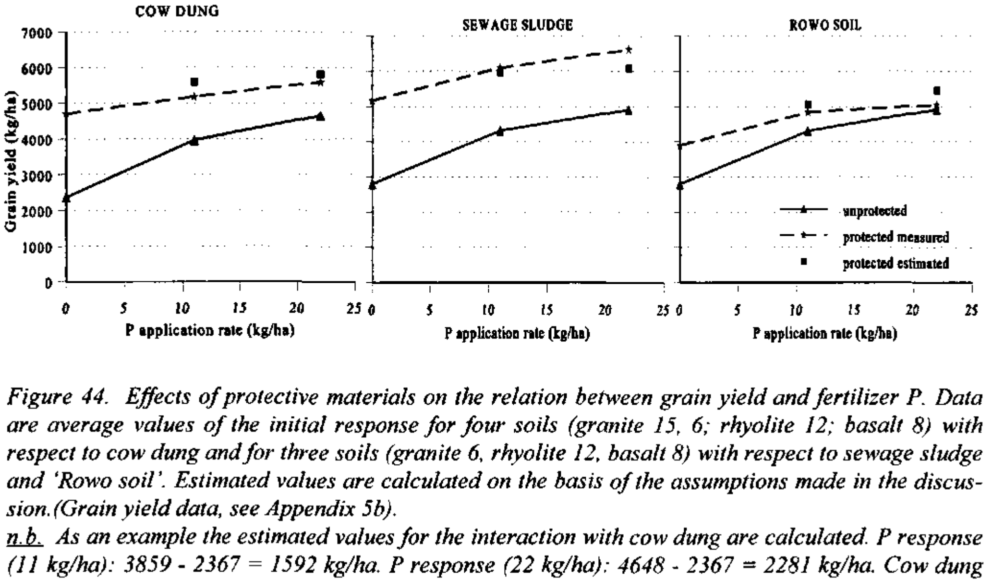


Figure 44. Effects of protective materials on the relation between grain yield and fertilizer P. Data are average values of the initial response for four soils (granite 15, 6; rhyolite 12; basalt 8) with respect to cow dung and for three soils (granite 6, rhyolite 12, basalt 8) with respect to sewage sludge and 'Rowo soil'. Estimated values are calculated on the basis of the assumptions made in the discussion.(Grain yield data, see Appendix 5b).

*n.b. As an example the estimated values for the interaction with cow dung are calculated. P response (11 kg/ha): 3859 - 2367 = 1592 kg/ha. P response (22 kg/ha): 4648 - 2367 = 2281 kg/ha. Cow dung response: 4703 - 2367 = 2336 kg/ha. Interactive response (11 kg/ha): 0.7 * 2336 + 1592 = 3227. Interactive response (22 kg/ha): 0,5 * 2336 + 2281 = 3449. Interactive grain yield (11 kg/ha): 2367 + 3227 = 5594. Interactive grain yield (22 kg/ha): 2367 + 3449 = 5816 kg/ha.*

As an example, the following calculation is made. Suppose the enriched volumina of the protective materials are 30 and 50 % at P rates of 11 and 22 kg/ha respectively. Suppose, further, that P uptake from the enriched part of the volume proceeds at the same rate as for unprotected subseed placement and that P uptake from the non-enriched volume of the protective material is not affected by the fertilizer. Then, grain yields for protected placement can be calculated. They are presented in Figure 44. They correspond fairly well to the experimental results.

The assumption in the example that uptake of fertilizer P with protection proceeded at the same rate as with (unprotected) subseed placement can be discussed further. P sorption within the protective materials might have been different from that in soil because protective materials and soil differ in their physical properties, such as moisture retention, and chemical properties. A negative interaction should result if P is retained in a smaller volume within protective material than in soil. This might have occurred as less fertilizer was recovered at an equal distance below the granules with protected subseed placement than with (unprotected) subseed placement. Alternately, a larger sorption volume will result in a positive interaction. Positive interactions may also result from a higher root density in the protective materials than in soil, which was observed in sewage sludge, or from the more favourable moisture retention characteristics of cow dung and sewage sludge, which favoured the functioning of roots during frequent short periods of drought. Which of these effects occurred and how they interacted in the trials remains a matter of speculation.

Since a positive interaction between triple superphosphate and protective materials was not found, there is no reason for recommending mantling of the fertilizer in protective materials, as was done in my experiments, for farming practice in preference to application of the fertilizer and protective materials together in the same plant hole.

8.3.6 Possible interactions with phosphate rock

The direct application of phosphate rock to tropical soils continuous to attract attention, as it is normally a cheaper way of adding fertilizer P (Warren, 1992). Application of phosphate rock has not been studied in my experiments for reasons mentioned in Chapter 5.3.1. However, the results give rise to some remarks. Triple superphosphate has the advantage that fertilizer P (about 80 %) dissipates from the granules, creating a volume of soil enriched with fertilizer P. Phosphate rock doesn't react so strongly with the soil as triple superphosphate. When applied in a similar granular form as triple superphosphate, a much smaller P-enriched soil volume will be created and, hence, a lesser initial response can be expected. Grinding phosphate rock and mixing it with the soil constituents will create a larger P-enriched soil volume or a larger surface area, so, allowing more roots to contribute to the P uptake, resulting in better crop responses. Residual effects of phosphate rock can be expected to last longer than those of acidulated phosphates because of the slower initial reactions and the less initial responses and plant recoveries. To allow a comparison to be made between triple superphosphate and phosphate rock as P fertilizer with respect to crop response, P recovery and economic effectiveness, simulation modelling in combination with long-term field experiments are necessary.

Summarising, the plant response to fertilizer P applications was regulated by the size and position of the P-enriched soil volume in relation to the position of the plant, and the mainly genetically-controlled root distribution pattern. It was suggested that the number of roots, i.e. root surface area, present in the small P-enriched volume was the limiting factor in fertilizer P uptake.

8.4 SOIL FERTILITY EVALUATION AND FERTILIZER P RECOMMENDATIONS

The results of the many field experiments showed consistently that the fertilizer P in the soil remained plant-available for at least three growing seasons, irrespective of the method of fertilizer application, P status and type of soil. This indicated that the somewhat rigid concept of P fixation, as defined in Chapter 4, was not appropriate for the soils in the Kisii area. The second 'slow' phase of the fixation process was shown to proceed at a very slow rate under field conditions. Thus, P fixation is much less of a problem for farmers than expected. A fairly constant fraction of the fertilizer P remained available to the maize crop and resulted in good initial and residual responses and, hence, in a gradually increasing cumulative plant recovery on soils with a low P status.
It also indicates that the method of P application, within certain P rate ranges, is not a critical factor for farming practice as far as yield response and P recovery are concerned. Recommendations can therefore be based on other farm management factors such as: available labour and capital, expected financial return on the fertilizer, side-effects of P application and the adaptability in the agricultural practice of the area.

Maximum maize yields obtained with P application differed largely between sites and soil types, most likely due to differences in rootability of the subsoil, available soil moisture and rainfall distribution. Differences between soil types in recovery of fertilizer P were much smaller than expected, from the huge variation in parent materials and soil types and the wide range in P-sorption capacities. Clearly, the number of field trials could have been reduced without losing much information. On the other hand, the wide variability in parent material, soil type, P-status and climate forms a good basis for applying the findings of the Kisii area to other tropical areas with similar geological conditions, soils and climate.

The extensive data-set may provide a basis for the development of recommendations for fertilizer application to soils with a low P status. The data suggest that a single 'heavy' P application of 66 to 131 kg/ha (in P_2O_5: 150 to 300 kg/ha) mixed in the tilled layer resulted in similar initial and residual yield responses and cumulative P recovery percentages as a single application of these rates placed below the seed. They also suggest that a single P application of 33 kg/ha (in P_2O_5: 75 kg/ha) below the seed resulted in similar initial and residual yield responses and cumulative P recovery percentages as three split applications of 11 kg/ha (in P_2O_5: 25 kg/ha) to three successive crops. However, more definite conclusions should be based on long-term field experiments in combination with mechanistic modelling. The data gathered in this study may prove suitable for the parameterization of these models.
Changes in the availability of fertilizer P in the soil with time can be effectively measured with Olsen's extract. However, the P-Olsen value was not a suitable parameter, or at least not as the only parameter, for determining the availability of native P in the soils with a low P status. In the Kisii area, total P formed a better parameter. In combination with the results from the studies in the Kilifi area of South East Kenya, the potential supply of native P to maize plants was related by Janssen & Van der Eijk (1990) to three parameters, namely: total P, P-Olsen and the pH of the soil, according to the equation:

$$SP = fp*0.013*\text{ total P} + 0.5*\text{P-Olsen}$$

where: SP = supply of P to a maize crop during one growing season, kg per ha,
fp= 1 - 0.5 (pH - 6), a correction factor related to $pH(H_2O)$ indicating that a $pH(H_2O)$ value of 6 is considered to be an optimum.
Total P and P-Olsen are expressed in mg/kg.

This relationship and similar relationships for N and K are used in the model for QUantative Evaluation of the Fertility of Tropical Soils (QUEFTS). This model can be used to predict yields of unfertilized soils and the possible response to N, P and K application (Janssen et al., 1986, 1989, 1990; Smaling & Janssen, 1993). The results of my study, together with the results from the Kilifi area and from Suriname, were used to develop QUEFTS.

Determining P-sorption isotherms and deriving the Standard P Requirements from this does not form a suitable basis for P application recommendation. With triple superphosphate, P was sorbed at higher levels and the assumption that in the entire tilled layer a P concentration of 0.2 mg/l is obtained after applying P according the Standard P requirements is not valid under field conditions. In fact, in the case of mixing, only a minor fraction of the soil volume is enriched with fertilizer, while the P concentration in the soil moisture in the P-enriched soil volume may exceed the level of 0.2 mg/l.

For agricultural practice, the low-input strategy is recommended. With maize, subseed placement at the start of each crop is recommended at a P rate of about 20 to 40 kg/ha (in P_2O_5: 45 to 90 kg/ha). At these rates, slightly more P is applied than plants require for producing maximum grain yields, and the P availability of the soils will gradually increase by enlarging the soil volume enriched with fertilizer P. Hence, the P-status of the soil is gradually restored and raised to a level, at which P is no longer yield-limiting. In the case of repeated subseed placement, plants benefit from both the starter-effect of the freshly-applied fertilizer and the residual effect of previously-applied (residual) fertilizer. Repeated subseed placement as well as single subseed placement at the recommended rates give farmers good financial returns (Appendix 10). In the case of repeated subseed placement at a P rate of 33 kg/ha, the average cumulative net returns were 3,800; 7,200 and 12,900 Kenyan shillings per ha after one, two and three crops respectively. For the Kisii area, where farmers are used to applying small amounts of cow dung in the plant hole, it is recommended that this practice be continued and that triple superphosphate be applied, either alone or together with cow dung, whereby mantling of the fertilizer in the cow dung, as was done in the trials for experimental reasons, is unnecessary.

SUMMARY

In tropical areas with high annual rainfall, the naturally well-drained soils usually have high concentrations of iron and aluminum hydroxides, low levels of available P and high P-fixation capacities. Consequently, P is often the major limiting factor in crop production on these soils and yield responses to fertilizer application and fertilizer P recoveries in the crop are usually low. Since, in many areas of the tropics, population growth is rapid and, in many tropical farming systems less fertilizer is applied to than nutrients are withdrawn from the soils, P often forms a constraint in food production.

To cope with P-fixation problems, insight is required into the major factors that control P fixation and the availability of fertilizer P and, thus, its recovery by plants. It is also important to know in which way these factors are affected by characteristic properties of fertilizers, soils, plants and climate. Basically, the fertilizer phosphate - soil - plant interactions are important.

The overall aim of the study was to improve our understanding of the fertilizer phosphate - soil - plant interactions and thereby to increase both the yield response to phosphate fertilizer and the recovery and utilization of fertilizer P in tropical soils with low levels of available P. More specifically, the objectives were as follows:
1. to analyze and describe the P status in dominant soil types of the Kisii area of South West Kenya and to relate this status to parent material and soil type;
2. to study the compositional changes of triple superphosphate fertilizer and fertilizer P transport and sorption in various soils under field conditions;
3. to test the efficacy of various methods of fertilizer P application with respect to initial and residual plant responses, using hybrid maize as a test crop;
4. to assess the short-term (one growing season) and mid-term (three growing seasons) plant recovery of fertilizer P for various soils; and
5. to establish a basis for improved recommendations of P fertilizer application with emphasis on the low-input strategy and using the high-input strategy as a reference.

Central to the study were the fertilizer - soil - maize plant interactions as encountered in the field. An integrated study involving laboratory and greenhouse experiments and extensive field experimentations was judged most appropriate for satisfying the objectives mentioned above. Experimental designs of the laboratory and field experiments were based on a literature review and a conceptual model of the behaviour of fertilizer P in tropical soil. No mathematical modelling was envisaged, simply because of the limited amount of knowledge of the fertilizer P behaviour in Kenyan soils at the start of the study, and because of time constraints. However, the results may be useful as input for modelling the complex interactions between fertilizer P, soil and plant under tropical field conditions.

The experimental work of this study was carried out between 1976 and 1980. For various reasons, beyond the scope of the project, the study was interrupted for many years. Yet, the results can be judged still relevant and, therefore, worth publishing.

Summary

Since P fixation is an ambiguous term, the following working definition has been chosen in this study. P fixation is defined as a process which starts with a rapid adsorption and precipitation of fertilizer P on soil constituents and eventually results in the transformation of fertilizer P into soil phosphate, with properties and behaviour similar to those of the native soil phosphate. Evidently, in agricultural practice, P fixation can only be a problem on soils with a low P status.

In order to improve the P availability in high P-fixing soils, two strategies have been suggested in the literature:
1. Quenching the P-fixation capacity by incorporating large amounts of phosphate into the tilled layer of the soil, thus creating a specific P concentration in the soil solution of the tilth necessary for optimum plant growth.
2. Placing small quantities of phosphate in the soil near the plant, thus creating such a P concentration in only a limited fraction of the solum in which the P-fixation capacity is quenched. This low-input strategy needs less fertilizer and, hence, less capital investment than the high-input strategy of incorporating large amounts of fertilizer in the tilled layer.

In the low-input strategy, use is made of the phenomenon that plants can adequately be supplied with P when only a small fraction of their rooting system is involved in P uptake. Furthermore, it is supposed that placement of phosphate quenches the P-fixation capacity in the soil surrounding the placed fertilizer and results in P concentrations in the soil solution of the fertilized soil volume exceeding those at which optimum P nutrition of crops is guaranteed. Due to a P-buffering capacity, it is further assumed that these high levels of P concentration are maintained in the small enriched soil volume over an extended period.

In order to create such conditions the following questions arise:
1. How can the P concentration in the soil solution surrounding the fertilizer be controlled to allow P uptake to proceed at an optimum rate? The P concentration should not be raised above the concentration at which the P uptake rate is at a maximum (C max) and should not fall below a critical concentration, and certainly not below a minimum concentration (C min) during a growing season.
2. What should be the size of soil volume affected by fertilizer granules to enable roots growing in this volume to absorb sufficient fertilizer P?
3. How much P fertilizer should be concentrated to sufficiently quench the P-fixation capacity of the soil immediately surrounding the fertilizer?
4. At what distance from seeds or plants and at what depth in the solum should the fertilizer be placed?
5. Should the fertilizer be concentrated at one location or split over more locations near the plant?
6. Should the fertilizer be concentrated in a single application or distributed over several applications during a growing season?
7. Which methods are available to avoid or delay the fixation of fertilizer P in the soil?

The present study was designed to address these questions. Since the low-input strategy is more appropriate than the high-input strategy to the small-scale farming system that exists in

many tropical areas and more appropriate in undulating areas with bad off-road connections, this study was focused on the low-input strategy.

Recommendations given in the literature such as: reducing the P-fixation capacity by applying lime or silicates prior to P application; improving P utilization by application of P in the form of organic material or phosphate rock, or by improving the mycorrhizal condition of the soil; or selecting plant cultivars or species capable of absorbing phosphate from soils with low levels of available P, were only reviewed. They were not applied in this study because they were not thought to be promising, given the soil properties and the limited availability of the materials in the area.

The field experiments were carried out in South West Kenya, in the Kisii area. They were conducted over three successive growing seasons, over about 600 days, from 1977 to 1979. They were carried out on arable land of farmers who grew subsistence (mainly maize) and cash crops on a small scale.

The treatments studied in the trials were:

- Placement of phosphate in the plant holes with a thin layer of soil in-between seed and fertilizer ("subseed placement"). This treatment was chosen because it allows rapid contact between fertilizer and seminal roots and is common among farmers.
- Placement of phosphate within protective materials such as locally-purchased cow dung, sewage sludge and a local soil high in native P, in order to delay or prevent the P fixation ("protected subseed placement").
- Placement of phosphate in two or four holes beside the plant hole in order to increase contact between fertilizer and the radially-developing permanent roots ("scattered placement").
- Placement of phosphate deeper in the tilth beside the plant hole in order to benefit from the better physical condition in the soil for P uptake during the frequent dry spells in the growing season ("deep placement").
- Placement of phosphate in plant holes below the seed, whereby an equal amount of P was applied at the start of each growing season ("repeated subseed placement"). This treatment was chosen because a combination of fresh and residual fertilizer is assumed to have a positive effect and because repeated subseed placement can be easily introduced in farming practice.
- Broadcasting and incorporation of phosphate throughout the tilled layer in a single application at the start of the experiments, as a reference for the high-input strategy ("mixing").

Triple superphosphate was used as P fertilizer. The P-application rates were: 5.5, 11, 22, 33, 44 and 131 kg/ha with placement, and 66, 131, 262, 524, 1,048 and 2,096 kg/ha with mixing. These wide ranges where chosen in order te be able to study the initial and residual responses during three successive growing seasons in these strongly P-sorbing soils. Protective materials were applied at a rate of 100 cm^3 per plant hole. Nitrogen was applied in all trials at equal rates. Other nutrients were not supplied as, in a parallel field trial, these were found not to limit grain yields. Fertilizer application, planting, weeding and harvesting were done manually similarly to the small-scale farming practice in the survey area. Mixing of fertilizer, however, was carried out with a rotary tiller.

Under the field conditions, the following processes were studied:
- Grain yield response to fertilizer P.
- P uptake and utilization during a growing season. P uptake and distribution within the plants were monitored and the utilization, i.e the amounts of grains produced per kg P, was calculated.
- Fertilizer P recovery. The apparent amounts recovered during three successive growing seasons were calculated.
- Early plant response to fertilizer P. Several shoot and root properties were measured during a growing season.
- The compositional changes of triple superphosphate granules after application in the soils. These changes were monitored with X-ray diffraction, X-ray microanalysis, optical microscopy, scanning electron microscopy and wet chemical analysis.
- The dissolution of fertilizer P and the subsequent transport and sorption in the soil. This was monitored by measuring total P in the residual fertilizer granules and in the soil surrounding the fertilizer granules several times after application.
- The availability of fertilizer P. This was monitored by measuring the available P fraction in the soil enriched with fertilizer and in the residual fertilizer granules, and by calculating the P recovery in the above-ground plant components.

The following results were obtained:

1 Soils and P-status

The soils in the Kisii area in South West Kenya were derived from various parent materials such as granite, rhyolite, basalt or felsite-andesite. All soils were influenced by quaternary ash deposits from Rift Valley volcanoes. On the basis of the occurrence of a mollic epipedon and/or an argillic subhorizon, they were classified as typic Paleudolls, oxic Argiudolls, Tropudults, or orthoxic Palehumults. They belong to the very fine to fine clayey, kaolinitic, isothermic to isohyperthermic soil families. According to the classification system of the FAO/UNESCO, the soils were classified as Nitisols and luvic Phaeozems. In a minor part of the Kisii area, at the eastern border, small areas exist where the soils were developed entirely in volcanic ashes. These soils were classified as pachic andeptic Hapludolls.

Most of the soils in the Kisii area are low in available P (P-Olsen) and have medium to high P-sorption capacities. Hence, crop production was limited by the low P status of the soils. If no P fertilizer was applied, the grain yields for the representative fields, averaged over three crops, were: 612 and 1,303 kg/ha (granite soils, Fields 6 and 15); 3,501 kg/ha (rhyolite soil, Field 12); 4,608 kg/ha (basalt soil, Field 8) and 5,647 kg/ha (felsite-andesite soil, Field 2) respectively. The fact that differences in P-Olsen values in these soils were small (ranging from 1.6 to 3.2 mg/kg) and total P values varied widely and were related to the grain yields, suggests that the differences in native P availability were mainly a result of differences in total P values. Total P values in the topsoil were: 549 and 490 mg/kg (granite soils); 675 mg/kg (rhyolite soil); 920 mg/kg (basalt soil) and 1,035 mg/kg (felsite-andesite soil) respectively. In the granite and rhyolite soils, the rootability of the argillic horizon in the subsoil was reduced and, hence, made these soils more susceptible to drought than the other soils. The presence of roots in the subsoil of these soils depended strongly on the occurrence of large biopores. Besides differences in total P values, this reduced rootability might have also contributed to the differences in yield both among the fields and within a field because of the spatial variability in biological activity.

The volcanic ash soils (Fields 10 and 11) served as reference soils in this study. They had high P-Olsen values (38 to 60 mg/kg), high total P contents (1,681 to 2,081 mg/kg) and low P-sorption capacities. Grain yields varied over three seasons from 4,946 to 7,859 kg/ha. Yield-limiting factors on these soils were low soil temperature, temporary N shortages, hail damage and lodging.

2 Compositional changes of triple superphosphate granules and P sorption in the soils

Monocalcium phosphate, the main component of triple superphosphate, rapidly dissolved after application in the fields. Three weeks after application, the dissolution was already complete, as was most of the dissipation into the soil and the sorption on the soil constituents. About 20 % of the fertilizer P remained in the residual granules in the form of brushite (dicalcium phosphate dihydrate), fluorapatite and an amorphous unidentified P compound. Brushite was mainly formed at the periphery of the granules. The presence of fluorapatite was assumed to be partly a result of an incomplete acidulation during the manufacture of the fertilizer and partly a result of new formation after dissolution of monocalcium phosphate and subsequent reactions, whereby the acid produced was neutralized by the soil constituents. The changes in composition of triple superphosphate were similar for different application methods, P application rates and soils, despite the large variations in P-sorption capacity and climate. Residual granules remained in the soils up to the end of the trials, about 600 days after application. They could be easily recovered with subseed placement, provided that the application sites had not been disturbed during the weedings and seedbed preparations. In the case of mixing, many residual granules were observed in the tilled layer, especially at high application rates, notwithstanding the seedbed preparations and weedings.

The fertilizer P that dissipated from the granules was sorbed in high amounts at short distances from the granules. With increasing P application rates, both the fertilizer P content and transport distance of fertilizer P in the soil increased. At a P rate of 131 kg/ha, P sorption reached a level of about 10,000 mg/kg in the first two centimetres of soil below the fertilizer granules. Steep penetration fronts of fertilizer P were not observed, although they were expected on the basis of the shapes of the P-sorption isotherms. Spatial variability in the soil with respect to porosity and chemical composition, non instantaneous sorption and changes in chemical composition of the passing solute were probably major factors causing this dispersion.

Because of the strong sorption, downward transport of fertilizer P was limited to the tilled layer. Even at the highest P application rates with placement (131 kg/ha) or mixing (1,024 and 2,048 kg/ha), and even on the reference volcanic ash soil with a low P-sorption capacity, no fertilizer P was recovered at a depth of 25 to 30 cm below the soil surface at the end of the trials.

Fertilizer P was sorbed to a much higher level (4 to 40 times) than expected on the basis of P-sorption studies in the laboratory. Furthermore, the P sorption in the field and laboratory were not related. The temporarily extreme chemical conditions in the field and the interference with calcium, a main component of triple superphosphate, were assumed to have caused this difference, rather than the difference in reaction time.

The form in which fertilizer P was sorbed in the field could not be discovered. Crystalline compounds were not detected and, with a few X-ray micro-analyses of soil particles attached to residual granules, no concentrations of P were found, not even in the periphery of the particles. Considering the Ca/P ratio in the P-enriched soil, Ca derived from the triple superphosphate probably played a role in the kind of P compounds formed.

It is concluded that dissolution, dissipation and sorption of the fertilizer P were dominated by the intrinsic properties of triple superphosphate, rather than by the chemical properties of the soils. Suggested explanations for the phenomenon that the initial rapid reactions were followed by a slow further transport and an apparently slow fixation of fertilizer P were the high porosity of the friable fine-structured soils, so that, in spite of the frequent showers, pores were often air-filled and the fact that transformation of brushite and fluorapatite into strengite and variscite is unlikely to occur.

3 *Efficacy of fertilizer application methods*

Application of P stimulated plant growth (including root growth), shortened the growing season and increased grain yields. Compared to the initial responses, good residual responses were found in the second and third season, even at the lower application rates, indicating that fertilizer P remained available up to at least the end of the trials, irrespective of the method of application, P status and type of soil.

Placement of P fertilizer induced a starter-effect. The start of the plant response corresponded with the moment plant roots reached the soil in the immediate surroundings of the fertilizer site. The moment at which the starter-effect appeared became later in the following order: subseed placement and protected subseed placement > scattered placement in two or four holes beside the seeds > deep placement beside the seeds. Notwithstanding the differences in the extent of the starter-effect, the eventual grain yields were similar for the different placement methods at an equal P-application rate of 22 kg/ha. Protected subseed placement yielded an additional effect of the protective material itself, especially if cow dung or sewage sludge were used. Protection of triple superphosphate with cow dung or sewage sludge in order to prevent contact between the fertilizer P and soil constituents was adequate at the rates used (P: 22 kg/ha, protective material: 100 cm^3/plant). At overlapping P application rates in the range of 44 to 131 kg/ha (in P_2O_5: 100 to 300 kg/ha), subseed placement and mixing in the tilled layer resulted in similar yield responses and P recoveries. At lower rates, for instance at a P rate of 22 kg/ha, subseed placement resulted, due to the starter-effect, in a better yield response and P recovery than mixing. A single P application of 33 kg/ha below the seed resulted in similar initial and residual yield responses and cumulative P recovery percentages as three split applications (repeated subseed placement) of 11 kg/ha to each of the three successive crops.

The yield maxima ranged from 3,074 to 10,293 kg/ha. They differed among the fields and within a field, and showed seasonal variation. Over three seasons, they ranged from 3,074 to 7,248 kg/ha {430 - 1,832 kg/ha} for the granite soils; from 4,890 to 10,293 kg/ha {2,792 - 4,892 kg/ha} for the rhyolite soils; from 6,804 to 8,609 kg/ha {3,979 - 4,908 kg/ha} for the basalt soils and from 6,079 to 9,731 kg/ha {5,433 - 7,337 kg/ha} for the felsite-andesite soils. The yields between the brackets refer to the ranges in grain yields without P application. The yield maxima were obtained with mixing at P application rates ≥ 524 kg/ha. At these rates, it was no longer P, but one or more of the following factors, that limited grain yield: temporary droughts, temporary N shortages and sometimes low soil temperature, lodging, hail damage or striga (witchweed) infections.
The differences in rootability of the subsoil and, hence, in the susceptibility to drought, might have contributed to the differences in yield maxima among the fields and also within a field, especially within the fields of the granite soils.

4 P utilization and recovery of fertilizer P

When P limited grain yield, the relationships between P in grain (x), P in above-ground plant components (y) and grain yield (z) could be described by the following equations: $y = 0.46+1.13x$ and $z = 620(y-0.50)$. Plants should be able to take up at least about 0,5 kg P per ha to develop the minimum required amount of plant tissue for producing grains. The efficiency of P utilization (z/y) increased from about 350 to 550 kg/kg after P application, up to rates of about 44 kg/ha. With fertilizer P, P was more efficiently utilized, as it improved ear-formation and kernel-filling, which resulted in an increased harvest index. With increasing P application rates, the efficiency of utilization gradually decreased to about 300 kg/kg at P rates above 524 kg/ha, as a result of a luxurious uptake of fertilizer P.

The cumulative apparently-recovered P fraction in plants after three crops was about 0.25 at an application rate of 22 kg/ha with subseed placement. With increasing application rates the apparent-recovery fraction decreased. At an application rate of 2,096 kg/ha, it was as low as about 0.02. The residual recoveries in the second and third seasons were not, or only slightly, lower than the initial recovery in the first season. The recovery fractions were about the same for all soils and hence, did not follow the differences in P-sorption capacities. Protection by mantling triple superphosphate granules in cow dung, sewage sludge or a soil rich in P had no effect on the recovery of fertilizer P.

5 P fertilizer application recommendation

The results of the many field experiments showed consistently that the fertilizer P in the soil remained plant-available for at least three growing seasons, irrespective of the method of fertilizer application, P status and type of soil. This indicated that the concept of P fixation, as defined in this study, was not appropriate for the soils in the Kisii area. The second 'slow' phase of the fixation process was shown to proceed at a very slow rate under field conditions. Thus, P fixation is much less of a problem for farmers than expected. A fraction of the fertilizer P remained available to the maize crop and resulted in good initial and residual responses and, hence, in gradually increasing cumulative plant recoveries in these soils with a low P status. It also indicates that the method of P application, within certain P rate ranges, is not a critical factor for farming practice as far as yield response and P recovery are concerned. Recommendations can therefore be based on other farm management factors such as: available labour and capital, expected financial return on the fertilizer, side-effects of P application and the adaptability in the agricultural practice of the area.

The availability of fertilizer P could be monitored by measuring the available P fraction. High P-Olsen values were found in the residual granules, in the P-enriched soil volume below the placed fertilizer (up to 800 mg/kg) and in the tilled layer with mixing. The ΔP Olsen values were related to the ΔP total contents. The available fraction (ΔP Olsen/ΔP total) was about 0.10 to 0.15 with both placement and mixing and remained fairly constant with time, notwithstanding differences in P-sorption capacities of the soils. Therefore, the P-Olsen value might be a suitable parameter for following the behaviour of fertilizer P in soils and to form a basis for predicting (residual) grain yield responses to fertilizer P for soils with low levels of available P and high P-fixation capacities.

Although part of the fertilizer P was easily extractable, the P recoveries were low and, often, the P uptake was not sufficient to produce maximum grain yields. The phenomenon that a sufficient uptake could only be obtained with relative large amounts of fertilizer was assumed to be a result of the plant root characteristics of maize in combination with the soil volume enriched with fertilizer P. It was suggested that the number of roots, i.e. root surface area or root length density, present in the small P-enriched volume was the limiting factor in fertilizer P uptake.

Since fertilizer P application only resulted in more and thicker roots and did not affect the maize root distribution pattern in the soil, the required fertilizer P uptake for producing maximum grain yields can only be obtained by creating a sufficiently large soil volume enriched with fertilizer within easy reach of the plant roots. This can be obtained by applying - triple superphosphate at a sufficiently high application rate. In this respect, triple superphosphate has an advantage over rock phosphate, as monocalcium phosphate dissolves and fertilizer P dissipates into the soil. With mixing, however, the major part of the P-enriched soil is not within easy reach for the roots, which results in a delayed crop response. Furthermore, mixing stimulates weed germination and growth and is, therefore, discouraged especially at high application rates, unless appropriate measures for weed control can be taken. In addition, high application rates result in an inefficient utilization of fertilizer P, due to a luxurious uptake.

In the case of subseed placement, increasing the application rates led to higher P sorption levels and, hence, to a less than proportional increase of the soil volume enriched with fertilizer P. At a P rate of 131 kg/ha, the P-enriched soil volume was still not sufficient to obtain the yield maxima. A further volume increase by applying higher P rates should be avoided, as a P rate of 131 kg/ha already carries the risk of fertilizer burn and results in unnecessarily high P contents in the soil surrounding the fertilizer.
Scattered placement and deep placement in several holes beside the seeds give the opportu-

nity to increase the application rate and, hence, to create sufficiently large P-enriched soil volumes without the hazards of fertilizer burn and unnecessarily high P contents in the soil surrounding the fertilizer. Scattered placement and deep placement are, however, rather laborious and not, therefore, viable options.

Therefore, repeated subseed placement of triple superphosphate at moderate P rates, avoiding immediate contact between seeds and fertilizer is recommended. When P fertilizer is applied at the start of each growing season, plants get a maximum benefit from the starter-effect from the fresh fertilizer and sufficient support during the growing season from the residual fertilizer in the soil beside the plants. P rates of about 20 to 40 kg/ha are recommended for maize. At these rates, more P is applied than plants require for producing maximum grain yields and the P availability of the soils will gradually increase by enlarging the soil volume enriched with fertilizer P. This repeated subseed placement fits in with the low-input strategy and is probably easily adaptable in tropical, small-scale farming systems. In addition, farmers can expect good financial returns on the fertilizer at these rates. Since the expected rapid P fixation did not occur, application methods based on preventing contact between fertilizer and soil constituents, such as mantling in cow dung, sewage sludge or in soil with a high P-status, are not necessary. However, cow dung and sewage sludge resulted in an additional yield response themselves. Therefore, the practice of applying cow dung in plant holes, as is done in the Kisii area, should be continued. Hence, application of cow dung and triple superphosphate, either alone or together in a plant hole, is also recommended, whereby mantling of the fertilizer in the cow dung, as was done in the trials for experimental reasons, is unnecessary.

Despite the good grain yield responses to high rates of incorporated fertilizer, the high-input strategy is not recommended. This strategy is not appropriate in small-scale farming systems especially in undulating areas such as in the Kisii Highlands. Tractors and rotary tillers, necessary for incorporating the fertilizer, require a relatively high capital investment, as well as the fertilizer itself, while capital is scarce. The financial return for a farmer on a heavy fertilizer application is low, and often limited by the various other factors than P determining the crop yield maxima, for instance the rootability of the subsoil and, hence, the susceptibility to drought, so that the possible response to P application cannot fully develop and the yield maxima may show large seasonal variation. Furthermore, highly qualified technical support and good off-road connections are needed. But, above all, the high-input strategy requires large amounts of phosphate fertilizer, especially if application rates, the standard P requirements (SPR), are based on the P-sorption capacity determinations in the laboratory. Although world phosphate resources are large, the reserves of premium-grade phosphate rock are small and running low, and they are actually scarce in the tropical regions. The high-input strategy accelerates the running-down of these resources, which is another reason for not recommending it.

The wide variability in parent material, soil type, P-status and climate forms a good basis for applying the findings of the Kisii area in other tropical areas with similar geological conditions, soils and climate. The extensive data-set may provide a basis for soil fertility evaluation and fertilizer P recommendations for soils with a low P status.

The P-Olsen values of the soils were very low, almost near the detection limit, while grain yields varied widely. Therefore, the P-Olsen value was not a suitable parameter, or at least not as the only parameter, for predicting the availability of native P in the soils with a low P status. In the Kisii area, total P formed a better parameter. In combination with the results from the studies in the Kilifi area of South East Kenya, the potential supply of native P to maize plants was related to three parameters, namely: total P, P-Olsen and the pH of the soil.

The results of my study, together with the results from the Kilifi area and from Suriname, were used to develop QUEFTS, which can be used to predict yields of unfertilized soils and the possible responses to N, P and K application.

In conclusion:

Fertilizer P was sorbed in the soil at a much higher level than predicted on the basis of P-sorption capacity determinations in the laboratory. Consequently, the fertilizer P-enriched soil volume was relatively small. Although, in this volume, a high level of available P (P-Olsen value) was maintained during at least three growing seasons (about 600 days), P remained yield-limiting, unless P was mixed in the tilled layer at a high rate. It was suggested that the number of roots, i.e. root surface area, present in the small P-enriched volume was the limiting factor in fertilizer P uptake.

The concept of P-fixation, as defined in this study, was not appropriate for the soils in the Kisii area. The second 'slow' phase of the fixation process was shown to proceed at a very slow rate under field conditions. Thus, P fixation is much less of a problem for farmers than expected.

For agricultural practice, the low-input strategy is recommended. With maize, subseed placement of triple superphosphate at the start of each crop is recommended at a P rate of about 20 to 40 kg/ha (in P_2O_5: 45 to 90 kg/ha). At these rates, slightly more P is applied than plants require for producing maximum grain yields, and the P availability of the soils will gradually increase by enlarging the soil volume enriched with fertilizer P. Hence, the P status of the soil is gradually restored and raised to a level at which P is no longer yield-limiting. In the case of repeated subseed placement, plants benefit from both the starter-effect of the freshly applied fertilizer and the residual effect of previously-applied (residual) fertilizer. For the Kisii area, where farmers are used to applying small amounts of cow dung in the plant hole, it is recommended that this practice be continued and that triple superphosphate be applied, either alone or together with cow dung, whereby mantling of the fertilizer in the cow dung is unnecessary.

SAMENVATTING

In tropische gebieden met een hoge jaarlijkse neerslag hebben de van nature goed drainerende bodems vaak hoge concentraties aan ijzer en aluminium oxiden en hydroxiden. In dergelijke bodems is de fosfaatbeschikbaarheid voor planten veelal gering en de fosfaatfixatiecapaciteit hoog. Fosfaat is daardoor veelal de belangrijkste opbrengst beperkende voedingsstof. Bovendien zijn de effecten van fosfaatbemesting op de opbrengst en de recoverie van het meststoffosfaat in planten doorgaans gering. Aangezien in veel tropische gebieden de bevolkingsdruk hoog is en in tropische landbouwsystemen doorgaans meer voedingsstoffen aan de bodem worden onttrokken dan via bemesting worden teruggegeven, vormen de teruglopende lage beschikbaarheid van het bodemfosfaat en de fixatie van meststoffosfaat vaak een belemmering voor de voedselproductie.

Om het fosfaatfixatieprobleem te kunnen oplossen, is inzicht nodig in de factoren die de fixatie en daarmee de lage beschikbaarheid en recoverie van meststoffosfaat bepalen. Verder is het van belang te weten op welke wijze de eigenschappen van meststoffen, bodems, planten, en het klimaat hierop invloed hebben. In wezen zijn de interacties tussen meststoffosfaat, bodem en plant van belang.

Het hoofddoel van deze studie was de interacties tussen meststoffosfaat, bodem, en planten beter te begrijpen en daardoor de gewasopbrengsten te verhogen en de recoverie en benutting van het meststoffosfaat in planten te verhogen. Meer specifiek waren de doelen:

1. Het inventariseren en analyseren van de P-status van de voor de landbouw meest belangrijke bodems in het Kisii gebied in zuidwest Kenia en het relateren van de P-status aan het geologisch moedermateriaal en het bodemtype.
2. Het bestuderen van de compositionele veranderingen van tripelsuperfosfaat na toediening in de bodem, alsmede het transport en de binding van het meststoffosfaat in de bodem onder veldomstandigheden.
3. Het testen van de effecten van verschillende bemestingsmethoden op de gewasopbrengsten, zowel wat betreft de directe werking als de nawerking. Hierbij werd maïs als testgewas gebruikt.
4. Het bepalen van de recoverie van meststoffosfaat in planten, zowel op de korte termijn (één groeiseizoen) als op de middellange termijn (drie groeiseizoenen).
5. Het ontwikkelen van een basis voor fosfaatbemestingsadviezen. Daarbij werd de studie gericht op de lage input strategie en werd de hoge input strategie als referentie gebruikt.

Centraal in de studie stonden de interacties tussen meststoffosfaat, bodem en maïs zoals die zich in het veld manifesteerden. Een geïntegreerde studie met laboratorium-, kas- en veldproeven werd het meest geschikt geacht voor het bereiken van de gestelde doelen. De opzet van de proeven werd gebaseerd op een literatuurstudie en een conceptueel model van het gedrag van meststoffosfaat in tropische bodems. Mathematische modellering is niet toegepast omdat de kennis van het gedrag van meststoffosfaat in Keniaanse bodems bij de start van de studie beperkt was, en mede vanwege beperkingen in tijd om deze modellen onder veldomstandigheden te testen. De resultaten van de studie kunnen echter bruikbaar zijn voor het modelleren van de complexe interacties tussen meststoffosfaat, bodem en plant onder veldomstandigheden in de tropen.

Het experimentele werk van deze studie werd uitgevoerd tussen 1976 en 1980. Om redenen, buiten het bereik van het project, werd de studie meerdere jaren onderbroken. Toch mogen de resultaten voor de huidige bemestingsproblematiek in de tropen nog steeds als belangrijk beschouwd worden en zijn derhalve waard om te publiceren.

Aangezien het begrip fosfaatfixatie op meerdere manieren wordt uitgelegd, is het in deze studie als volgt omschreven. Fosfaatfixatie is een proces dat start met een snelle adsorptie en precipitatie van meststoffosfaat aan en op de bodembestanddelen en dat uiteindelijk leidt tot een transformatie van meststoffosfaat in bodemfosfaat, met eigenschappen en gedrag die overeenkomen met het oorspronkelijke bodemfosfaat. Het moge duidelijk zijn dat voor de landbouwpraktijk fosfaatfixatie alleen een probleem kan vormen op bodems met een lage P-status.

Om de fosfaatbeschikbaarheid van bodems met een hoge fosfaatfixatiecapaciteit te verbeteren worden in de literatuur twee strategieën aanbevolen:

1. Inwerken van grote hoeveelheden fosfaat in de gehele bouwvoor. Op deze wijze wordt beoogd de fosfaatfixatiecapaciteit van de bodem te verzadigen en daardoor een zodanig verhoogde P-concentratie in het bodemvocht van de bouwvoor tot stand te brengen dat een optimale gewasgroei mogelijk wordt.
2. Plaatsen van geringe hoeveelheden fosfaat bij de planten. Op deze wijze wordt beoogd de fosfaatfixatiecapaciteit in slechts een klein deel van het bodemvolume van de bouwvoor te verzadigen. Deze lage input strategie vraagt minder meststof en daardoor een lagere kapitaalinvestering dan de hoge input strategie, waarbij grote hoeveelheden fosfaatmeststof in de bouwvoor worden ingewerkt.

Bij de lage input strategie wordt verondersteld dat planten voldoende fosfaat kunnen opnemen wanneer slechts een klein gedeelte van het wortelstelsel bij de fosfaatopname betrokken is. Bovendien wordt verondersteld dat bij plaatsen van fosfaatmeststof de fosfaatfixatiecapaciteit van het deel van de bodem in de omgeving van de meststof wordt verzadigd en dat dit zal leiden tot P-concentraties in het bodemvocht van dit deel van de bodem die het niveau voor een optimale P-opname overschrijden.
Verder wordt verondersteld dat deze optimale P-concentraties in het kleine bemeste bodemvolume, vanwege de P-buffercapaciteit van de bodem, over een lange periode in stand blijven.

Om deze omstandigheden in de bodem te kunnen creëren, doen zich de volgende vragen voor:

1. Hoe kan de P-concentratie in het bodemvocht rondom de meststof zo worden beheerst dat de P-opname met een optimale snelheid kan plaatsvinden? Daarbij dient rekening gehouden te worden met het feit dat de P-concentratie niet zover verhoogd zou moeten worden dat deze boven het niveau komt te liggen waarop de P-opname met maximale snelheid (C-max) verloopt en anderzijds niet zover verlaagd zou moeten worden dat deze onder een kritisch niveau komt te liggen, en zeker niet onder de minimumconcentratie (C-min) gedurende een groeiseizoen.
2. Wat zou het bodemvolume moeten zijn dat met meststoffosfaat aangerijkt moet worden om

de plantenwortels in dit volume in staat te stellen om voldoende meststoffosfaat op te nemen? 3. Hoeveel meststof moet worden geplaatst om de fosfaatfixatiecapaciteit van de bodem in de onmiddellijke omgeving van de meststof in voldoende mate te kunnen verzadigen?

4. Op welke afstand van de zaden of planten en op welke diepte in de bodem zou de meststof moeten worden geplaatst?
5. Zou de meststof moeten worden geconcentreerd op één plaats of uitgesplitst over meerdere plaatsen nabij de plant?
6. Zou de meststof moeten worden geconcentreerd in een eenmalige gift of verdeeld over meerdere giften gedurende een groeiseizoen?
7. Welke methoden zijn beschikbaar om de fixatie van meststoffosfaat in de bodem te voorkomen of te vertragen?

Het ontwerp van deze studie was gericht op het kunnen beantwoorden van dergelijke vragen. Aangezien de lage input strategie voor kleinschalige landbouwsystemen en voor geaccidenteerd gebieden met een slechte weginfrastructuur zoals die in veel tropische gebieden voorkomen beter geschikt is dan de hoge input strategie, werd deze studie gericht op de lage input strategie.

De in de literatuur gegeven aanbevelingen zoals: het reduceren van de fosfaatfixatiecapaciteit door het bekalken van de bodem of het gebruik van silikaten voorafgaand aan de fosfaatbemesting; het verbeteren van de fosfaatbenutting door het toedienen van fosfaat in de vorm van organisch materiaal of ruwfosfaat; het verbeteren van de groeiomstandigheden voor mycorrhiza's; of door het selecteren en kweken van plantensoorten die beter in staat zijn om P uit een bodem met een lage P-status op te nemen, zijn in deze studie beschouwd. Ze zijn evenwel niet toegepast omdat deze aanbevelingen naar verwachting niet zouden voldoen, gelet op de bodemeigenschappen, of het niet of beperkt voorhanden zijn van de benodigde materialen in het gebied.

De veldproeven werden verricht in het Kisii gebied in zuidwest Kenia. Zij werden uitgevoerd gedurende drie aaneengesloten groeiseizoenen over ongeveer 600 dagen in de periode van 1977 tot 1979. De velden werden aangelegd op de akkers van boeren die op kleine schaal voedingsgewassen (voornamelijk maïs) en handelsgewassen verbouwden.

In de veldproeven werden de volgende behandelingen bestudeerd:

- Het plaatsen van fosfaat onder het zaad met een laagje grond tussen meststof en zaad "subseed placement". Deze behandeling werd gekozen omdat hierbij de primaire wortels snel in contact zouden kunnen komen met het meststoffosfaat en deze manier van bemesten onder de boeren in het gebied gebruikelijk was.
- Het plaatsen van fosfaat in beschermende materialen zoals lokaal verkrijgbare koemest, rioolwaterzuiveringsslib, en een van nature fosfaatrijke grond. Hiermede zou de fosfaatfixatie kunnen worden voorkomen of vertraagd "protected subseed placement".
- Het plaatsen van fosfaat in twee of vier gaten naast het zaad "scattered placement". Hierbij zouden de zich radiaal ontwikkelende permanente wortels snel in contact kunnen komen met het meststoffosfaat.

- Het plaatsen van fosfaat dieper in de bouwvoor naast het zaad "deep placement". Door de betere fysische omstandigheden zouden de plantenwortels bij deze methode beter in staat kunnen zijn om het meststoffosfaat op te nemen gedurende de vele kortdurende droge perioden in een groeiseizoen.
- Het plaatsen van fosfaat onder het zaad, waarbij aan de start van elk groeiseizoen een gelijke hoeveelheid fosfaat werd gegeven "repeated subseed placement". Deze behandeling werd gekozen omdat een combinatie van verse en residuaire meststof een positief effect zou kunnen hebben en omdat deze behandeling gemakkelijk in de bestaande landbouwpraktijk kan worden ingevoerd.
- Het breedwerpig strooien en inwerken van fosfaat in de bouwvoor in de vorm van een eenmalige toediening aan het begin van de veldproeven "mixing". Deze behandeling werd gekozen als referentie voor de hoge input strategie.

Als fosfaatmeststof werd tripelsuperfosfaat gebruikt. De meststof werd in de volgende hoeveelheden P toegediend: 5,5; 11; 22; 33; 44 en 131 kg/ha bij plaatsing en 66; 131; 262; 524; 1.048 en 2.096 kg/ha bij breedwerpig strooien en inwerken. Deze ruime bandbreedtes werden gekozen om in deze sterk fosfaatfixerende bodems in staat te zijn de initiële en residuaire effecten gedurende drie seizoenen te kunnen bestuderen. De beschermende materialen werden toegediend in een hoeveelheid van 100 cm^3 per plant. Stikstof werd in alle proeven in gelijke hoeveelheden toegediend. Andere plantenvoedende stoffen werden niet toegediend, aangezien deze in een parallel lopende veldproef niet opbrengst beperkend bleken te zijn in deze bodems. Bemesten, zaaien, wieden en oogsten werden handmatig gedaan overeenkomstig de lokale agrarische praktijk. Een uitzondering werd gemaakt voor het breedwerpig gestrooide fosfaat. Dit werd ingewerkt met een frees.

Onder de veldomstandigheden werden de volgende processen bestudeerd:
- De effecten van de fosfaatbemesting op de maïskorrelopbrengsten.
- De fosfaatopname en benutting gedurende een groeiseizoen. De fosfaatopname en de distributie binnen de planten werden gevolgd en de benutting, i.c. de hoeveelheid geproduceerd graan per kilo P werd berekend.
- De recoverie van het meststoffosfaat. De schijnbare hoeveelheid opgenomen meststoffosfaat werd berekend per seizoen en geaccumuleerd over drie seizoenen.
- De effecten van fosfaatbemesting op de vegetatieve ontwikkeling van maïsplanten. Meerdere blad-, stengel- en worteleigenschappen werden gemeten gedurende een groeiseizoen.
- De compositionele veranderingen van tripelsuperfosfaatkorrels na toediening in de bodem. Deze veranderingen werden gevolgd met X-ray diffractie, X-ray micro-analyse, optische microscopie, scanning electronen microscopie en nat-chemische analyse.
- Het oplossen en het vrijkomen van het fosfaat uit de tripelsuperfosfaatkorrels en het transport van het meststoffosfaat in de bodem. Dit werd gevolgd door meting van het P-totaal gehalte in de residuaire meststofkorrels en in de grond in de omgeving van de meststofkorrels op meerdere tijdstippen na toediening.
- De beschikbaarheid van het meststoffosfaat. Deze werd gevolgd door meting van het beschikbaar fosfaat (P-Olsen en P-water) in de residuaire meststofkorrels en in het met fosfaat aangerijkte bodemvolume, alsmede door de bepaling van de fosfaatrecoverie in de bovengrondse plantendelen.

De volgende resultaten werden verkregen:

1 Bodems en P-status

De bodems in het Kisii gebied in zuidwest Kenia zijn ontwikkeld in verschillende moedermaterialen, zoals graniet, rhyoliet, basalt en felsiet-andesiet. Alle bodems zijn in meer of mindere mate beïnvloed door kwartaire asafzettingen van vulkanen in de Rift-Vallei. Op basis van het voorkomen van een "mollic epipedon" en/of een "argillic subhorizon" zijn de bodems geklassificeerd als "typic Paleudolls, oxic Argiudolls, Tropudults, of orthoxic Palehumults". Zij behoren tot de zeer fijn tot fijn kleiige, kaolinietische, isothermische tot isohyperthermische bodemfamilies. Volgens het FAO/UNESCO bodemklassificatiesysteem behoren ze tot de "Nitisols" en de "luvic Phaeozems". In een klein deel van het Kisii gebied, aan de oostgrens, komen in kleine eenheden bodems voor die geheel in vulkanische as ontwikkeld zijn. Deze bodems zijn geklassificeerd als "pachic andeptic Hapludolls".

Met uitzondering van de vulkanische asbodems hebben de bodems in het Kisii gebied een geringe hoeveelheid beschikbaar fosfaat (lage P-Olsen waarden) en matige tot hoge P-bindingscapaciteiten. Dientengevolge werden de korrelopbrengsten beperkt. Indien P-bemesting achterwege bleef, werden de volgende gemiddelde korrelopbrengsten voor de representatieve bodems gevonden: 612 en 1.303 kg/ha (granietbodems, velden 6 en 15); 3.501 kg/ha (rhyolietbodem, veld 12); 4.608 kg/ha (basaltbodem, veld 8) en 5.647 kg/ha (felsiet-andesietbodem, veld 2). Het feit dat de P-Olsen waarden slechts varieerden tussen 1,6 en 3,2 mg/kg en de P-totaal gehalten een aanzienlijke variatie vertoonden en correleerden met de korrelopbrengsten, veronderstelt dat de fosfaatbeschikbaarheid in hoge mate samenhangt met het totaal P-gehalte van de bodem. De P-totaal gehalten in de bouwvoor van de bodems waren achtereenvolgens: 549 en 490 mg/kg (granietbodems, velden 6 en 15); 675 mg/kg (rhyolietbodem, veld 12); 920 mg/kg (basaltbodem, veld 8); 1.035 mg/kg (felsiet-andesietbodem, veld 2).
In de graniet en rhyoliet bodems bleek de bewortelbaarheid van de klei-inspoelingslaag ("argillic horizon") in de ondergrond beperkt te zijn. Deze bodems zijn daardoor meer droog-tegevoelig dan de overige bodems. De aanwezigheid van wortels in de ondergrond bleek doorgaans samen te gaan met het voorkomen van grote bioporiën, die, vanwege de ruimtelijke variabiliteit in biologische activiteit, een onregelmatige spreiding in de bodem vertoonden. Naast de verschillen in P-totaal gehalten, kan deze beperkte bewortelbaarheid bijgedragen hebben aan de verschillen in de korrelopbrengsten tussen de velden, en de ruimtelijke variabiliteit in bewortelbaarheid aan de verschillen binnen een veld.

De vulkanische as bodems (velden 10 en 11) dienden in deze studie als referentiebodems. Zij hebben hoge P-Olsen waarden (38 en 60 mg/kg), hoge P-totaal gehalten (2.081 en 1.681 mg/kg) en lage P-bindingscapaciteiten. De korrelopbrengsten varieerden over de drie seizoenen tussen 4.946 en 7.859 kg/ha. Opbrengst limiterende factoren bij deze bodems waren de lage bodemtemperatuur, tijdelijke stikstof tekorten, hagelschade en legering als gevolg van windvlagen.

2 Compositionele veranderingen van tripelsuperfosfaatkorrels en P-binding in de bodem.

Monocalciumfosfaat, het hoofdbestanddeel van tripelsuperfosfaat, bleek in de veldproeven in de bodem snel op te lossen en te reageren met de bodembestanddelen. Drie weken na toediening was het oplossen voltooid, evenals het merendeel van de verplaatsing in de bodem en de binding van het meststoffosfaat aan de bodembestanddelen. Ongeveer 20 % van het meststoffosfaat bleef achter in de residuaire korrels in de vorm van brushiet (dicalciumfosfaatdihydraat), fluorapatiet en een amorfe -niet geïdentificeerde- fosfaatverbinding. Brushiet werd hoofdzakelijk gevormd in de periferie van de korrels. De aanwezigheid van fluorapatiet was waarschijnlijk gedeeltelijk een gevolg van een onvolledige zuurbehandeling bij de productie van de meststof en gedeeltelijk van nieuwvorming bij het oplossen van monocalciumfosfaat en de daarop volgende reacties, waarbij het geproduceerde zuur werd geneutraliseerd door de bodembestanddelen. De veranderingen in samenstelling van de tripelsuperfosfaatkorrels waren bij de verschillende bemestingsmethoden, P-giften en bodems overeenkomstig, ondanks grote verschillen in P-bindingscapaciteiten en klimaat. Residuaire korrels bleven in de bodems bestaan tot het einde van de veldproeven, ongeveer 600 dagen na toediening. Zij konden gemakkelijk worden herkend en verzameld bij de plaatsingsbehandelingen, zolang ze niet waren verplaatst tijdens het wieden en de grondbewerkingen voor het zaaien. Bij de mengbehandelingen konden veel residuaire korrels worden waargenomen in de bouwvoor, in het bijzonder bij de hoge menggiften. Dit ondanks het regelmatige wieden en de grondbewerkingen voor het zaaien.

Het meststoffosfaat dat bij het oplossen van monocalciumfosfaat uit de korrels vrijkwam, werd in grote hoeveelheden in de bodem gebonden en tot over een korte afstand verspreid. Met toenemende P-gift namen zowel het P-totaal gehalte als de afstand, waarover het meststoffosfaat in de bodem werd verplaatst, toe. Bij een P-gift van 131 kg/ha bereikte de P-binding een niveau van ongeveer 10.000 mg/kg in de eerste 2 cm van de bodem onder de meststofkorrels. Scherpe verspreidingsfronten van het meststoffosfaat werden niet waargenomen. Dergelijke fronten konden worden verwacht op basis van de vorm van de P-bindingsisothermen. De belangrijkste oorzaken van deze dispersie waren waarschijnlijk de ruimtelijke variabiliteit in porositeit en chemische eigenschappen van de bodem, de niet instantane binding van het meststoffosfaat aan de bodembestanddelen, alsmede de veranderingen in de chemische samenstelling van de passerende oplossing.
Door de sterke binding bleef het neerwaarts transport beperkt tot de bouwvoor. Zelfs bij de hoogste P-giften bij plaatsen (131 kg/ha) en mengen (1.024 en 2.048 kg/ha), en zelfs in de vulkanische asbodems met een lage P-bindingscapaciteit, werd geen meststoffosfaat gevonden op een diepte van 25 tot 30 cm beneden het maaiveld aan het einde van de veldproeven.

Het meststoffosfaat werd tot in veel hogere gehalten (4 tot 40 maal) gebonden dan kon worden verwacht op basis van de fosfaatbindingsstudies in het laboratorium. Bovendien bleek de fosfaatbinding in het veld niet gerelateerd te zijn aan die in het laboratorium. De tijdelijke extreme chemische omstandigheden in het veld en de interferentie met calcium, een hoofdbestanddeel van tripelsuperfosfaat, worden verondersteld deze verschillen in hoofdzaak te hebben veroorzaakt. In vergelijking daarmee wordt verondersteld dat de bijdrage van het verschil in reactietijd tussen veld- en laboratoriumomstandigheden gering is geweest.

De vorm waarin het meststoffosfaat in de bodem onder veldomstandigheden werd gebonden kon niet worden bepaald. Kristallijne verbindingen werden niet waargenomen en met enkele

X-ray micro-analyses van bodembestanddelen liggend tegen residuaire korrels werden geen concentraties van meststoffosfaat gevonden, zelfs niet in de periferie van deze bestanddelen. Gezien de Ca/P ratio in het met P verrijkte bodemvolume heeft Ca afkomstig van het tripelsuperfosfaat waarschijnlijk een rol gespeeld in de aard van de gevormde fosfaatverbindingen.

Samenvattend wordt gesteld dat het oplossen, verplaatsen en het binden van het meststoffosfaat aan de bodembestanddelen meer bepaald werden door de intrinsieke eigenschappen van tripelsuperfosfaat dan door de chemische eigenschappen van de bodem. Het verschijnsel dat de eerste snelle reacties werden gevolgd door een langzaam verder transport en een schijnbaar langzame fixatie van meststoffosfaat wordt onder meer verklaard uit de hoge porositeit van de "friable fine-structured" bodems, waardoor, ondanks de vele regenbuien, de poriën vaak met lucht gevuld waren en uit het feit dat de transformatie van brushiet en fluorapatiet naar strengiet en varisciet onwaarschijnlijk is.

3 Effecten van de methoden van fosfaatbemesting

Fosfaatbemesting stimuleerde de plantengroei (inclusief de wortelgroei), verkorte het groeiseizoen en vergrootte de korrelopbrengst. In vergelijking tot het initiële effect op de korrelopbrengst, werden goede residuaire effecten in het tweede en derde groeiseizoen gevonden, zelfs bij lage P-giften. Dit wees op het beschikbaar blijven van fosfaat tot het einde van de veldproeven, ongeacht de bemestingsmethode, de P-status van de bodem en het bodemtype.

Het plaatsen van fosfaat veroorzaakte een "starter-effect". Het tijdstip waarop het effect begon, viel samen met het moment waarop de plantenwortels de grond in de directe omgeving van de meststofkorrels bereikten. Het tijdstip was afhankelijk van de wijze van plaatsen en kwam later in de volgende volgorde: "subseed placement" en "protected subseed placement" > "scattered placement" op twee of vier plaatsen > "deep placement" op twee plaatsen. Ondanks de verschillen met betrekking tot het "starter-effect", waren de korrelopbrengsten ongeveer gelijk voor de verschillende plaatsingsbehandelingen bij een gelijke P-gift van 22 kg/ha.

Beschermd plaatsen ("protected subseed placement") veroorzaakte een extra effect van de beschermende materialen zelf, in het bijzonder wanneer koemest en rioolslib werden gebruikt. Bescherming van tripelsuperfosfaat met koemest of rioolslib teneinde contact tussen meststoffosfaat en grond te voorkomen, bleek afdoende te zijn bij de toegepaste hoeveelheden (P: 22 kg/ha, beschermend materiaal: 100 cm^3/plant).

Plaatsen en mengen van meststoffosfaat resulteerden bij overlappende P-giften van 44 tot 131 kg/ha (in P_2O_5: 100 tot 300 kg/ha) in overeenkomstige korrelopbrengsten en P-recoveries. Bij lagere giften, bijvoorbeeld 22 kg/ha, leidde plaatsen ("subseed placement"), vanwege het "starter-effect", tot een hogere opbrengst en P-recoverie dan mengen.

Een eenmalige P-gift van 33 kg/ha geplaatst in het plantgat ("subseed placement") resulteerde in overeenkomstige initiële en residuaire effecten en cumulatieve P-recoveries als drie afzonderlijke P-giften van elk 11 kg/ha aan de drie achtereenvolgende maïsgewassen ("repeated subseed placement").

De maximale opbrengsten varieerden van 3.074 tot 10.293 kg/ha. Ze verschilden tussen de velden als ook binnen een veld en vertoonden seizoenschommelingen. Over de drie seizoenen varieerden zij van 3.074 tot 7.248 kg/ha {430 - 1.832 kg/ha} voor de granietbodems; van 4.890 tot 10.293 kg/ha {2,792 - 4,892 kg/ha} voor de rhyolietbodems; van 6.804 tot 8.609 kg/ha {3.979 - 4.908 kg/ha} voor de basaltbodems en van 6.079 tot 9.731 kg/ha {5.433 - 7.337 kg/ha} voor de felsiet-andesietbodems. De opbrengsten tussen accolades refereren aan de variaties in opbrengsten zonder P-bemesting. De maximale opbrengsten werden bereikt met mengen bij P-giften ≥ 524 kg/ha. Bij deze giften was het niet langer P, maar waren het één of meerdere van de volgende factoren, die de opbrengsten beperkten: tijdelijke droogtes, kortdurende N tekorten, lage bodemtemperatuur, hagelschade, legering als gevolg van windvlagen, of "striga" (heksenkruid) infecties. De verschillen in de bewortelbaarheid van de ondergrond en daardoor in droogtegevoeligheid van de bodems, zou bijgedragen kunnen hebben aan de verschillen in de maximale opbrengsten tussen de velden en binnen een veld, in het bijzonder binnen de velden van de granietbodems.

4 Fosfaatbenutting en recoverie van meststoffosfaat

Zolang P de korrelopbrengsten reguleerde bleek er een nauwe relatie te bestaan tussen de hoeveelheid P opgeslagen in de korrels (x), de totale hoeveelheid P opgenomen in de bovengrondse plantendelen (y) en de korrelopbrengst (z). De relaties konden worden beschreven met de vergelijkingen: $y = 0{,}46+1{,}13x$ en $z = 620(y-0{,}5)$. Om maïskorrels te kunnen produceren, moeten de planten tenminste 0,5 kg P per ha opnemen voor het vormen van de minimaal benodigde hoeveelheid stengel- en bladweefsel.
De efficiëntie van de P-benutting (z/y) nam toe van ongeveer 350 tot 550 kg/kg na toediening van meststoffosfaat in giften tot ongeveer 44 kg/ha. Na bemesting werd P efficiënter benut als gevolg van een betere kolfvorming een korrelvulling, hetgeen resulteerde in een hogere korrelindex. Met toenemende P-giften nam de efficiëntie van de P-benutting, als gevolg van een luxe opname van het meststoffosfaat, geleidelijk af tot ongeveer 300 kg/ha bij P-giften groter dan 524 kg/ha.

De cumulatieve schijnbare meststoffosfaatrecoverie in de planten na drie seizoenen bedroeg ongeveer 0,25 bij een P-gift van 22 kg/ha bij plaatsen. Met toenemende P-giften nam de recoveriefractie af. Bij een P-gift van 2.096 kg/ha was deze slechts ongeveer 0,02. De residuaire recoveries in het tweede en derde seizoen waren niet of slechts in geringe mate lager dan de initiële recoverie in het eerste seizoen. De recoveriefracties waren vrijwel gelijk bij de verschillende bodems en correleerden derhalve niet met de verschillen in de P-bindingscapaciteiten. Bescherming van het meststoffosfaat door het te omhullen met koemest, rioolslib of met fosfaatrijke grond, had geen effect op de recoverie van het meststoffosfaat.

5 Fosfaatbemestingsadviezen

De resultaten van de vele veldproeven waren consistent voor wat betreft het aantonen van het feit dat het meststoffosfaat in de bodems beschikbaar bleef voor de planten gedurende tenminste drie seizoenen, ongeacht de methode van toediening, de P-status van de bodem, het bodemtype en de klimatologische omstandigheden. Hiermede is duidelijk geworden dat het concept van de fosfaatfixatie, zoals gedefinieerd in deze studie niet van toepassing is op de bodems in het Kisii gebied. Blijkbaar verloopt de tweede langzame fase van het fixatieproces zeer langzaam onder veldomstandigheden. Fosfaatfixatie is derhalve veel minder een probleem voor de boeren dan was verwacht. Een fractie van het meststoffosfaat bleef beschikbaar voor de maïsplanten en resulteerde in goede initiële en residuaire effecten op de korrelopbrengsten, en derhalve, in geleidelijk toenemende cumulatieve P-recoveries in deze bodems met een lage P-status. Tevens bleek dat de methode van fosfaatbemesting, binnen een bepaalde bandbreedte aan P-giften, voor de landbouwpraktijk geen kritische factor vormt, zolang de effecten op de korrelopbrengsten en de P-recoveries in beschouwing worden genomen. Bemestingsadviezen kunnen derhalve worden gebaseerd op andere managementfactoren, zoals beschikbare arbeid en kapitaal, verwachte financiële meeropbrengsten, bijwerkingen van P-bemesting en de inpasbaarheid in het landbouwsysteem van de streek.

De plantenbeschikbaarheid van het meststoffosfaat kon worden gevolgd door meting van de beschikbare fractie. Hoge P-Olsen waarden werden gevonden in de residuaire korrels, in de bodem direct onder het geplaatste meststoffosfaat (tot waarden van 800 mg/kg) en in de bouwvoor met gemengd meststoffosfaat. De ΔP-Olsen waarden bleken te zijn gecorreleerd met de ΔP-totaal gehalten. De beschikbare fractie (ΔP-Olsen/ΔP-totaal) was ongeveer 0,10 tot 0,15, zowel bij plaatsen als mengen, en bleef tamelijk constant in de tijd, ondanks de verschillen in P-bindingscapaciteiten tussen de bodems. De P-Olsen waarde zou derhalve een geschikte parameter kunnen zijn voor het volgen van het gedrag van meststoffosfaat in de bodem en voor het bieden van een basis voor het voorspellen van de (residuaire) opbrengsteffecten van P-bemesting in tropische bodems met van nature lage P-Olsen waarden en hoge P-fixatiecapaciteiten.

Ofschoon een deel van het meststoffosfaat gemakkelijk kon worden geëxtraheerd, bleven de P-recoveries laag en was de P-opname vaak onvoldoende om de maximale korrelopbrengsten te halen. Het verschijnsel dat een voldoende opname pas kon worden bereikt bij hoge P-giften wordt toegeschreven aan de worteleigenschappen van maïs in combinatie met het bemeste bodemvolume. Verondersteld wordt dat het aantal wortels, i.c. worteloppervlak of wortellengtedichtheid, aanwezig in het geringe met P bemeste bodemvolume de beperkende factor is in de opname van meststoffosfaat.

P-bemesting resulteerde weliswaar in meer en dikkere wortels, maar had geen invloed op het bewortelingspatroon. De voor maximale korrelopbrengsten benodigde P-opname kon alleen worden bereikt door het creëren van een voldoende met meststoffosfaat verrijkte bodemvolume nabij de plant. Dit kan worden bereikt door tripelsuperfosfaat toe te dienen in een voldoende hoge gift. In dit opzicht heeft tripelsuperfosfaat een voordeel boven ruwfosfaat, omdat het meststoffosfaat door het oplossen van monocalciumfosfaat in de bodem wordt verspreid. Bij mengen in de bouwvoor bevindt het merendeel van het meststoffosfaat zich echter niet in de directe nabijheid van de planten, hetgeen resulteert in een vertraagd effect op de plantengroei of anders gezegd in het niet optreden van het "starter-effect". Bovendien stimuleert mengen de kieming en groei van onkruid. Mengen wordt derhalve ontraden in het bijzonder in hoge giften, tenzij geschikte onkruidbestrijdingsmaatregelen kunnen worden getroffen. Daarbij komt dat hoge P-giften, vanwege een luxe P-opname, tot een inefficiënte benutting van het meststoffosfaat leidt.

Bij toenemende giften leidde het plaatsen van meststoffosfaat tot hogere P-gehalten in de

bodem en daardoor tot een niet proportionele toename van het met meststoffosfaat verrijkte bodemvolume. Bij een P-gift van 131 kg/ha was het verrijkte bodemvolume echter nog niet voldoende om de maximale korrelopbrengsten te behalen. Het toediening van hogere P-giften ter vergroting van het volume wordt ontraden, aangezien een gift van 131 kg/ha in het plantgat ("subseed placement") al risico's geeft op wortelschade en bij deze gift onnodig hoge P-gehalten in de bodem rondom de meststofkorrels ontstaan.
Plaatsen op meerdere locaties naast het plantgat ("scattered placement" en "deep placement") biedt wel de mogelijkheid om, zonder de risico's van wortelschade, met hogere P-giften een groter bodemvolume te verrijken zonder dat onnodig hoge P-gehalten in de bodem ontstaan. Daartegenover staat dat deze bemestingsmethoden bewerkelijk zijn en daardoor minder geschikt zijn.

Gezien het bovenstaande wordt aanbevolen tripelsuperfosfaat in matige hoeveelheden bij aanvang van elk groeiseizoen in het plantgat te plaatsen ("repeated-subseed placement"). Daarbij dient direct contact met het maïszaad te worden voorkomen. De planten profiteren dan maximaal van het "starter-effect" van de vers geplaatste meststof onder het zaad en ondervinden verder in het groeiseizoen ondersteuning van de residuaire meststof terzijde van de planten. Voor maïs worden P-giften van ongeveer 20 tot 40 kg/ha aanbevolen. Bij deze P-giften wordt meer P toegediend dan de planten nodig hebben om de maximale korrelopbrengsten te behalen en wordt de plantenbeschikbaarheid vergroot door het stapsgewijze vergroten van het met P verrijkte bodemvolume. Deze methode past in de lage input strategie en is waarschijnlijk gemakkelijk inpasbaar in tropische kleinschalige landbouwsystemen. Bovendien kunnen boeren goede financiële meeropbrengsten verwachten bij deze P-giften.

Aangezien de verwachte snelle P fixatie niet optrad, zijn methoden gericht op het vermijden van het contact tussen meststoffosfaat en grond, zoals omhullen met koemest, rioolslib of met van nature fosfaatrijke grond, niet nodig. Koemest en rioolslib gaven echter zelf een extra korrelopbrengst. Dit is een goede reden om de bestaande praktijk in het Kisii gebied, waarin koemest in kleine hoeveelheden in de plantgaten van de gewassen wordt toegediend, te continueren. Derhalve wordt toediening van koemest in het plantgat, alleen of tezamen met tripelsuperfosfaat, eveneens aanbevolen, waarbij omhullen van de meststof met koemest, zoals in de veldproeven op experimentele gronden werd gedaan, niet nodig is.

Ondanks de goede effecten van het mengen van grote hoeveelheden meststoffosfaat in de bouwvoor op de korrelopbrengst wordt deze methode niet aanbevolen. Deze strategie is namelijk minder geschikt voor kleinschalige landbouwsystemen, in het bijzonder in heuvelachtige gebieden zoals in de "Kisii Highlands". Tractoren en rotor-eggen benodigd voor het inwerken van de meststof vragen een relatief hoge kapitaalinvestering, alsmede veel fosfaatmeststof, terwijl kapitaal schaars is. De financiële verdienste voor een boer van een hoge menggift is laag en wordt vaak beperkt door één van de vele andere factoren dan P die de maximale korrelopbrengsten in de praktijk kunnen bepalen, bijvoorbeeld de bewortelbaarheid van de ondergrond en daarmee de droogtegevoeligheid van de bodem, waardoor het mogelijke effect van P-bemesting zich niet volledig kan ontwikkelen en de maximale opbrengsten grote seizoensverschillen kunnen vertonen. Verder vraagt deze strategie een hoog gekwalificeerde technische ondersteuning en een goede weginfrastructuur. Maar bovenal vraagt deze strategie grote hoeveelheden fosfaatmeststof, in het bijzonder indien de giften worden gebaseerd op de in het laboratorium bepaalde P-bindingscapaciteiten, de "standard P requirements (SPR)". Ofschoon de fosfaatvoorraden in de wereld groot zijn, zijn de reserves van kwalitatief goede ruwfosfaten beperkt. Met name in de tropen zijn de kwalitatief goede ruwfosfaten schaars. De hoge-input strategie versnelt het verbruik van deze voorraden, hetgeen een extra reden is om deze strategie niet aan te bevelen.

De ruime variatie in moedermateriaal, bodemtype, P-status van de bodems en klimaat in het studiegebied vormen een goede basis voor toepassing van de onderzoeksresultaten in andere tropische gebieden met vergelijkbare omstandigheden als in zuidwest Kenia met betrekking tot geologie, bodem en klimaat. De uitgebreide gegevensset kan een goede basis bieden voor bodemvruchtbaarheidsevaluaties en P bemestingsadvisering voor bodems met een lage P-status.

De P-Olsen waarden van de bodems waren erg laag, nabij de detectielimiet, terwijl de korrelopbrengsten een grote spreiding vertoonden. De P-Olsen waarde is daarom geen geschikte parameter, tenminste niet als de enige parameter, om de beschikbaarheid van het bodemfosfaat te voorspellen. Voor het Kisii gebied bleek P-totaal een betere parameter te zijn. In combinatie met de resultaten van de studies in het Kilifi gebied in zuidoost Kenia, kon de potentiële beschikbaarheid van bodemfosfaat voor maïsplanten gerelateerd worden aan drie parameters, namelijk: P-totaal, P-Olsen en de pH van de bodem.

De resultaten van mijn studie, tezamen met die van het Kilifi gebied en Suriname, zijn gebruikt om het model "QUEFTS" te ontwikkelen. Dit model kan worden gebruikt om de opbrengsten te voorspellen van onbemeste bodems, alsmede de mogelijke opbrengsteffecten van N, P en K bemesting.

Concluderend:

Meststoffosfaat werd tot veel hogere gehalten in de bodems gebonden dan was voorspeld op basis van de P-bindingscapaciteiten, zoals die in het laboratorium waren bepaald. Als gevolg hiervan was het volume van de bodem dat werd verrijkt met meststoffosfaat gering. Hoewel in dit volume het meststoffosfaat goed beschikbaar bleef gedurende tenminste drie seizoenen (ongeveer 600 dagen) was P toch opbrengst beperkend, tenzij P in hoge giften in de bouwvoor werd gemengd. Verondersteld is dat het aantal wortels, i.c. het worteloppervlak of de wortellengtedichtheid, dat aanwezig was in het geringe met P verrijkte bodemvolume de beperkende factor vormde in de P-opname.

Het concept van de fosfaatfixatie, zoals gedefinieerd in deze studie, bleek niet van toepassing te zijn op de bodems in het Kisii gebied. De tweede langzame fase in het fixatieproces verloopt onder veldomstandigheden blijkbaar met een zeer lage snelheid. Fosfaatfixatie is daardoor veel minder een probleem voor boeren dan bij aanvang van de studie verwacht werd.

Voor de landbouwpraktijk wordt de lage input strategie aanbevolen. Voor maïs wordt geadviseerd elk seizoen tripelsuperfosfaat in het plantgat toe te dienen in een gift van ongeveer 20 tot

40 kg/ha (in P_2O_5: 45 tot 90 kg/ha). Bij deze giften wordt in geringe mate meer P aan de planten gegeven dan benodigd is voor het behalen van maximale korrelopbrengsten en neemt de P-beschikbaarheid toe door een stapsgewijze vergroting van het met P verrijkte bodemvolume. Hierdoor wordt de P-status van de bodem geleidelijk hersteld en gebracht op een niveau waarbij P niet langer meer opbrengst beperkend is. Indien bij de aanvang van elk groeiseizoen fosfaatmeststof in het plantgat geplaatst wordt profiteren de planten zowel van het "startereffect" van het vers toegediende fosfaat als van het residuaire effect van het in de vorige seizoenen geplaatste fosfaat. Voor het Kisii gebied waar de boeren gewend zijn om koemest in kleine hoeveelheden in het plantgat toe te dienen wordt aanbevolen deze praktijk voort te zetten. Toediening van koemest in het plantgat, alleen of tezamen met tripelsuperfosfaat, wordt eveneens aanbevolen, waarbij het omhullen van de meststof met koemest niet nodig.

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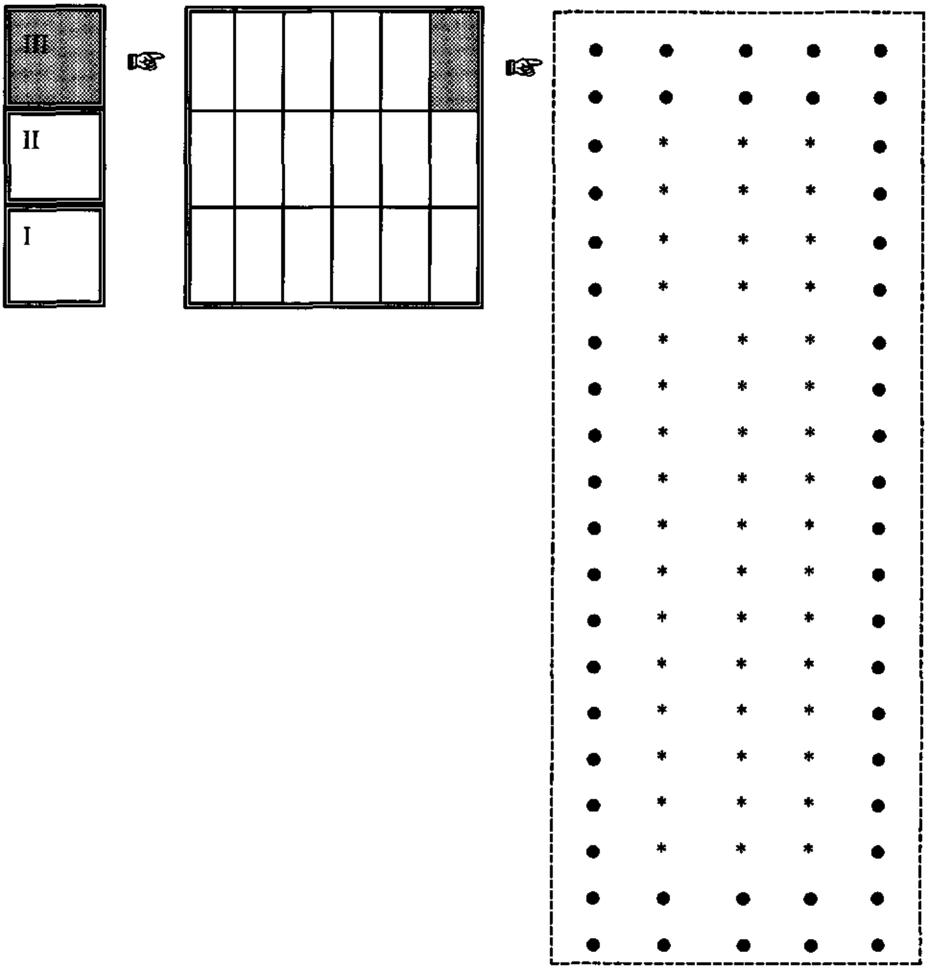
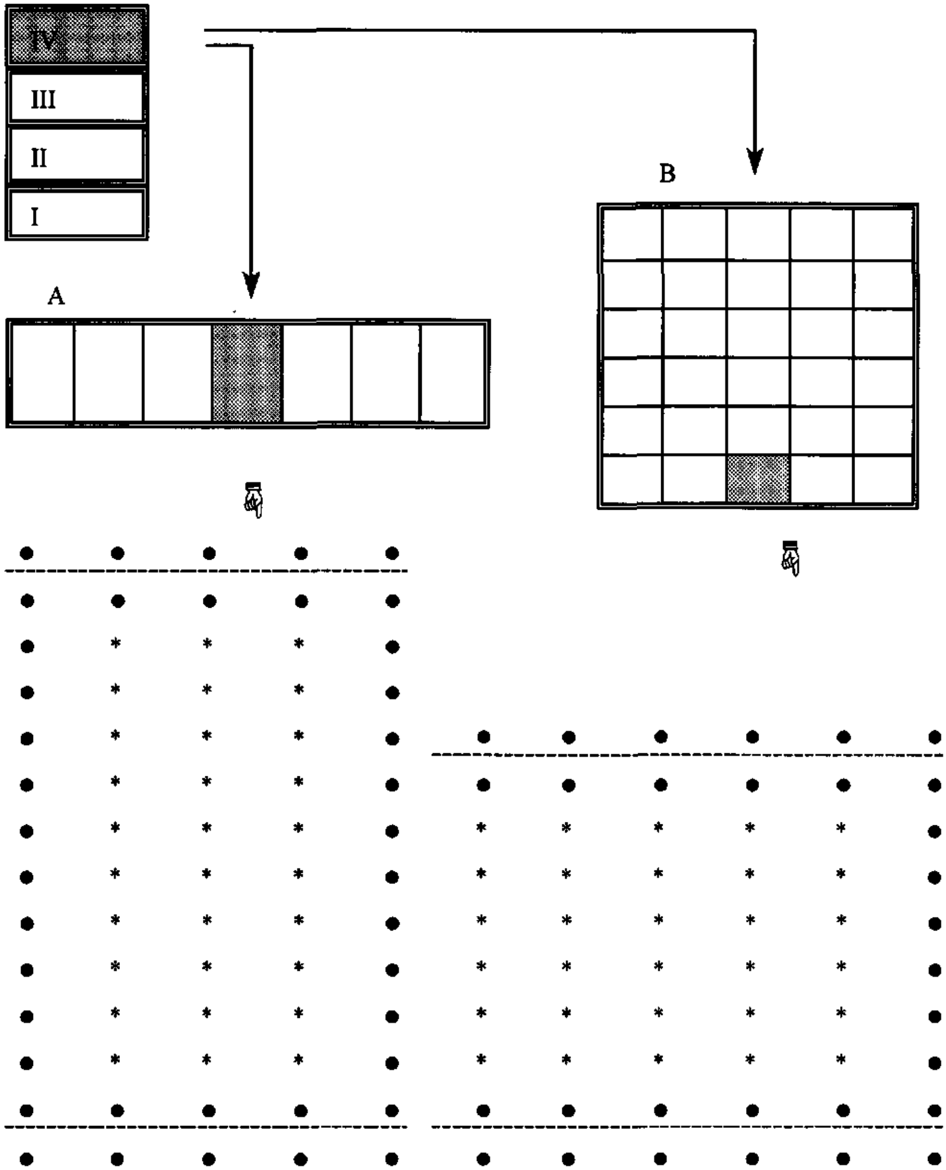
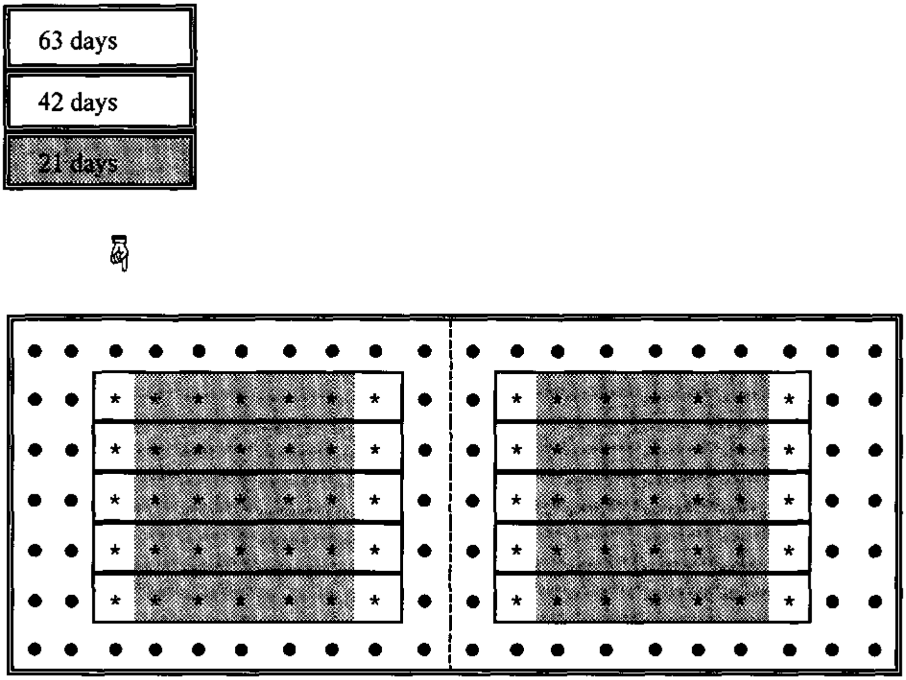


*Appendix 1. Lay out of the trials started in the first season on eleven fields; three replicates; eighteen treatments within each replicate; positions of net plants (*) and buffer plants (●) within a replicate (plot). Plot size: 3 * 6 m.*



*Appendix 2. Lay out of the trials started in the second season on six fields; four replicates; (A) and (B) replicates of a small and large trial respectively; position of net plants (*) and buffer plants (●) within a plot. Plot size: 2.4 * 3.6 m.*



Appendix 3. Lay out of the trials started in the third season on five fields to study early plant development with placement of fertilizer at 21, 42 and 63 days after planting: (*) treated plants; (shaded) net plants; (●) buffer plants. The same lay out was used to study the fertilizer P behaviour in the absence of plants.

Appendix 4. Grain yield data (kg/ha)

Treatment				Mixing							Subseed placement			Repeated subseed placement	
P rate (kg/ha)		0	0*	66	131	262	524	524*	1048	2096	22	44	131	11	33
Granite 15	season 1	609	786	2081	3153	4609	4611	4716	4659	5760	2240	2765	3782	1349	2551
	season 2	1208	1558	2782	3149	3824	4360	4990	4904	5527	2910	3465	3817	3126	3834
	season 3	1499	2157	3909	4800	5462	5069	5330	4966	6486	3065	4821	5388	4133	5632
Granite 6	season 1	1235	800	3133	3853	3837	3890	4126	3874	4221	2392	3537	3353	2520	2351
	season 2	430	258	2497	3442	3527	3074	4116	3478	4274	1645	3289	2771	2515	2784
	season 3	609	341	2869	4181	4336	4687	4999	4520	4382	2149	3711	3599	3354	3302
Granite 4	season 1	1435	1342	3354	3304	4193	5691	5515	5129	7248	1259	2043	2410	1816	2501
	season 2	1832	742	4236	4317	4106	4618	4705	5512	5335	1904	2958	3852	3081	3465
Rhyolite 12	sesaon 1	4272	4026	8332	8136	9364	9384	9907	10293	9747	5710	6957	8321	5262	6951
	season 2	2792	3540	4710	5016	6055	6377	6308	6696	6450	3898	4213	5085	4468	5219
	season 3	3188		6010	5910	6599	6785		7238	6642	4159	4627	6018	6235	6343
Rhyolite 13	season 1	4892	5127	5025	4390	5160	6010	5936	5678	7257	5358	5600	5269	5695	5612
	season 2	2997	3734	3119	3524	4553	4870	4944	4467	5566	2980	3098	4175	3753	4207
Basalt 8	season 1	4265	4439	7884	8264	7460	8609	8835	7924	8501	6398	7100	8521	5846	7078
	season 2	4618	5163	6316	6595	7059	6804	8197	7196	7563	5246	5909	6094	6225	6289
	season 3	4006	5157	5825	7649	7181	7577	7848	7262	8249	5128	5765	6935	5881	6800
Basalt 3	season 1	4908	5214	7625	6724	6831	7409	6868	7545	7492	6253	6882	6566	5748	6207
	season 2	3979	4650	6472	6076	6835	6962	6681	7389	7704	4446	5380	5986	5507	6433

Treatment				Mixing							Subseed placement			Repeated subseed placement	
P rate (kg/ha)		0	0*	66	131	262	524	524*	1048	2096	22	44	131	11	33
Felsite-andesite 2	season 1	5944	5409	8682	7979	8399	9002	8017	9262	9731	7478	7922	8007	7420	8270
	season 2	5433	5373	5991	6405	6142	6273	6428	6961	6088	5980	6126	6574	5965	6461
	season 3	5995	5795	6965	7642	7902	8187	7839	8818	9228	7046	6755	7391	7642	7962
Felsite-andesite 7	season 1	7337	7267	7564	8384	8462	8302	8427	8430	8968	8069	8124	8479	7457	8049
	season 2	6020	6109	6091	5996	6079	7300	6964	7118	7915	6256	6347	6575	6666	6479
Volcanic ash 10	season 1	7362	7556	6982	7584	7197	7534	7286	7789		7922	8409	6894	6765	7513
	season 2	5925	6259	5777	6460	5488	6437	5563	6195		6191	5974	6039	5996	6194
Volcanic ash 11	season 1	7859		8948			8310				8321		8218	7865	8395
	season 2	4946	5511	4923	5227	4909	5290	5113	5023		4838	5131	5334	5192	5315

(*) with application of K, Mg, S, Zn, Cu, B and Mo at the start of the first season

Appendix 5a. Grain yield data (kg/ha): season 2, initial response; season 3, residual response.

Treatment			Subseed placement			Scattered placement		Deep placement
P rate (kg/ha)		0	5.5	11	22	2*11	4*5.5	2*11
Granite 15	season 2	1071		2918	3848	3678	3577	2850
	season 3	1762		2956	3929	4782	4948	3280
Granite 6	season 2	1599		2728	3871	4148	3910	2410
	season 3	2353		2928	3503	3986	3401	3003
Rhyolite 12	season 2	2350	4296	3927	3864	4244	4379	3546
	season 3	1605	3646	3836	4915	5145	5710	4630
Basalt 8	season 2	4448	5977	6264	7010	6970	6034	5997
	season 3	4449	4872	4845	5665	6114	5276	5880
Felsite-andesite 2	season 2	5619	6530		7576	6738	6800	6512
	season 3	6080	5955		7082	7947	6693	6745
Volcanic ash 11	season 2	5799	6114		6731			

Appendix 5b. Grain yield data (kg/ha): season 2, initial response; season 3, residual response.

Treatment		Cow dung			Sewage sludge			Rowo soil		
P rate (kg/ha)		0	11	22	0	11	22	0	11	22
Granite 15	season 2	3685	5145	4914						
	season 3	2271	4304	4256						
Granite 6	season 2	3080	3312	4392	3697	4475	4905	2445	4007	4385
	season 3	2219	2647	3829	3734	3710	4414	3127	3074	3672
Rhyolite 12	season 2	4477	4461	4849	4831	5479	5981	3441	3770	3579
	season 3	3384	5375	6094	4336	6281	5623	3578	4150	4649
Basalt 8	season 2	7571	7783	8176	6954	8321	8966	5779	6718	7171
	season 3	4486	6428	6814	5177	5526	6383	4672	5524	6464

Appendix 6. P concentration (mmol/kg) in grain.

Treatment			Subseed placement			Mixing			
P rate (kg/ha)		0	22	44	131	66	131	524	2,096
Granite 15	season 1	62	53	59	56	65	67	75	85
	season 2	65	56	60	58	61	75	76	95
	season 3	66	49	57	56	64	66	89	91
Granite 6	season 1	67	66	62	77	72	82	87	127
	season 2	65	51	53	60	65	66	83	99
	season 3	56	58	58	70	62	77	79	105
Rhyolite 12	season 1	61	52	67	68	66	74	99	103
	season 2	61	51	62	60	65	63	68	90
	season 3	68	59	68	76	68	89	84	100
Basalt 8	season 1	57	51	51	53	59	62	67	82
	season 2	59	68	61	66	69	68	70	91
	season 3	62	62	59	75	64	78	89	104
Felsite-andesite 2	season 1	83	80	78	86	86	88	94	111
	season 2	65	68	68	70	65	79	84	97
	season 3	79	82	78	93	81	95	97	106
Volcanic ash 11	season 1	103	106		112		107	109	
	season 2	100	100	108	113	99	102	102	

Appendix 7. Early plant development after P application for five soils. P rates with subseed placement were: 0, 22, 44 and 131 kg/ha. (Sl), sewage sludge; (Cd), cow dung; (Sca), scattered placement in two holes, P rate 22 kg/ha; (Dp), deep placement in two holes, P rate 22 kg/ha.

Plant property		Dry matter (kg/ha)			Plant height (cm)			Plant diameter (mm)			Number of leaves			Leaf width (mm)			Number of root whorls in crown			Number of permanent roots			Number of roots per whorl (1)			Root width class (2)		G(3) (cm)	Plant sample size		
Time (day)		21	42	63	21	42	63	21	42	63	21	42	63	21	42	63	21	42	63	21	42	63	21	42	63	42	63	63	21	42	63
Granite 6	0	29	318	1126	34	85	146	7	16	18	6	12	13	25	64	77	2	5	7	9	20	35	5	4	5	2	4	72	10	6	6
	22	56	615	3008	41	109	198	9	19	22	7	12	15	42	82	92	3	5	7	12	25	48	5	5	8	3	7	128	10	6	5
	44	58	817	2701	40	118	192	9	22	21	7	13	15	37	91	100	3	5	8	11	28	49	5	6	7	3	6	119	10	6	5
	131	63	1064	4997	39	129	234	9	24	26	7	13	16	38	89	107	3	5	8	11	30	55	5	5	7	3	5	183	10	6	5
	Sl	41	627	2750	36	118	206	8	20	21	7	13	15	35	82	104	2	5	7	11	27	46	5	5	7	3	5	147	9	6	5
	Sl22	64	1263	4297	42	138	227	10	22	25	8	14	17	40	92	198	3	5	7	12	31	54	5	6	8	3	7	170	11	6	5
	Cd	43	740	2848	37	118	194	8	20	22	7	12	14	35	82	99	2	5	7	9	25	42	4	5	6	3	6	120	9	6	5
	Cd22	69	1047	3745	43	127	202	10	23	26	7	13	16	40	95	107	3	5	7	11	26	46	5	5	7	3	7	133	10	6	5
	Sca	31	754	2480	36	114	188	8	20	29	7	13	14	30	86	96	2	6	7	10	30	50	5	5	7	3	5	124	10	6	5
	Dp	31	650	2038	31	109	181	7	19	19	6	12	14	27	81	86	2	5	7	9	22	41	5	5	6	3	5	111	10	6	5
Rhyolite 12	0,00	17	119	906	30	59	123	6	12	18	6	10	12	21	45	76	2	4	7	7	15	33	5	4	5	1	3	39	11	6	5
	22	54	662	2783	41	105	180	10	20	26	7	12	15	42	78	100	3	5	8	11	27	47	5	6	7	3	6	97	12	6	5
	44	52	715	3055	43	107	183	10	21	24	7	13	15	42	83	101	3	5	8	11	26	52	5	5	6	3	5	127	12	6	5
	131	79	1031	4854	45	123	225	11	23	27	8	12	16	50	89	110	3	5	8	12	29	55	4	5	8	3	7	159	12	6	5
	Sl	42	584	2226	37	101	187	9	20	22	7	12	15	35	75	91	2	5	7	11	23	44	5	5	6	3	4	111	12	6	5
	Sl22	109	1193	3974	47	131	204	12	24	27	8	13	16	50	91	103	3	5	7	14	32	56	5	6	8	3	6	149	12	6	5
	Cd	39	547	2783	36	99	183	9	20	22	7	11	15	35	82	92	2	5	7	10	23	46	5	5	6	3	4	117	12	6	5
	Cd22	83	930	4427	48	119	225	12	24	27	8	13	16	50	87	107	3	5	7	14	28	50	5	5	8	3	6	167	12	6	5
	Sca	34	633	3301	35	106	187	9	20	26	7	12	16	34	78	100	2	5	7	10	24	55	4	5	8	3	6	126	10	6	5
	Dp	29	491	1903	29	92	180	7	18	21	7	11	14	27	68	84	2	4	7	7	20	39	4	4	6	2	5	104	12	6	5

Plant property		Dry matter (kg/ha)			Plant height (cm)			Plant diameter (mm)			Number of leaves			Leaf width (mm)			Number of root whorls in crown			Number of permanent roots			Number of roots per whorl (1)			Root width class (2)		G(3) (cm)	Plant sample size		
Time (day)		21	42	63	21	42	63	21	42	63	21	42	63	21	42	63	21	42	63	21	42	63	21	42	63	42	63	63	21	42	63
Basalt 8	0,00	20	186	680	31	66	115		14	22	5	11	12		58	84	2	4	6	9	18	27	5	5	5	2	3	20	9	6	5
	22	41	424	1827	38	86	160		21	26	7	12	14		79	107	2	5	6	11	21	33	5	5	6	2	5	62	9	6	5
	44	39	618	2826	38	100	197		23	27	6	12	15		85	113	2	5	6	10	23	40	5	5	8	3	6	118	10	6	5
	131	40	767	3070	38	104	193		24	31	6	12	15		96	114	2	5	7	10	26	42	4	5	6	3	5	109	9	6	5
	Sl	32	339	1574	35	79	162		19	24	6	11	13		70	97	2	4	6	10	20	32	5	5	6	2	5	55	10	6	5
	Sl22	27	854	2837	34	107	186		26	30	6	12	14		97	116	2	5	7	10	28	42	4	5	7	3	5	100	10	6	5
	Cd	34	396	1866	36	85	170		19	26	6	11	14		76	102	2	5	6	8	21	36	5	5	7	2	5	66	9	6	5
	Cd22	45	739	2745	41	101	186		24	29	7	12	15		93	118	2	5	7	10	26	42	5	6	7	3	5	94	10	6	4
Felsite-andesite 2	0,00	18	178	1095	28	58	132		16	30	5	10	13		59	102	2	4	6	8	20	31	4	5	6	2	4	25	10	8	5
	22	22	325	2253	30	73	167		20	36	6	11	14		72	118	2	4	7	9	22	43	4	5	8	3	6	58	11	7	5
	44	26	335	2277	31	74	167		19	36	6	11	14		76	127	2	4	7	10	29	40	4	5	8	3	6	55	11	6	5
	131	27	386	3153	31	77	183		21	38	6	11	16		77	133	2	5	6	11	22	41	5	5	9	3	7	77	12	7	5
Volcanic ash 11	0,00	14	279	1278	25	71	145		16	28	6	11	13		66	99	2	4	6	8	21	41	4	5	8	3	4		8	6	6
	22	15	427	1532	22	76	149		20	29	4	11	13		73	99	2	5	6	7	22	32	4	5	8	3	5		9	6	6
	44	14	345	1815	23	78	156		18	31	4	11	13		72	104	2	5	6	6	22	37	4	5	9	3	5		7	6	5
	131	10	381	1576	18	77	148		19	29	4	11	13		71	100	1	5	6	6	22	33	4	4	8	3	5		10	6	7

(1) number of roots in first, third and fifth whorl at 21, 42, 63 days after planting respectively.
(2) root width classes: (1) 1.0-1.5 mm; (2) 1.5 - 2.0 mm; (3) 2.0 - 2.5 mm; (4) 2,5 - 3.0 mm; (5) 3.0 - 3.5 mm; (6) 3.5 - 4.0 mm; (7) 4.0 - 5.0 mm.
(3) internal growing point of the shoot.

Appendix 8. Soil profile descriptions

Field 6	Local petrography: Kitere and Oyugis granites	Soil: orthoxic Paleuhumult	Date: 10-03-1979

Profile 1:

A1 0 - 25 cm
dark reddish brown (5YR 3/3, moist); moderate, very fine and fine subangular blocky; many very fine, common fine and few medium pores; friable; slightly sticky and slightly plastic; many very fine and many fine roots; clear and smooth transition to:

A3 25 to 54 cm
dark reddish brown (2.5YR 3/4, moist); strong, very fine subangular and very fine angular blocky; common very fine and few fine pores; friable; slightly sticky and slightly plastic; few very fine and few fine roots; gradual and smooth transition to:

B1 54 - 108 cm
dark reddish to reddish brown (2.5YR 3/4 (4/4), moist; moderate, very fine angular blocky; moderately thick continuous cutans; common very fine and few fine pores; friable; slightly sticky and slightly plastic; very few very fine roots.

B2t 108^{+} cm
dark red (2.5YR 3/6, moist); moderate, very fine angular blocky; moderately thick continuous cutans; common very fine and few fine pores; friable; slightly sticky and slightly plastic; no roots.

R 255 to > 320 cm

Profile 2:

Ap 0 - 15 cm
dark reddish brown to reddish brown (5YR 3.5/4, moist); moderately weak, fine and medium subangular blocky; few very fine and few fine pores; very friable; slightly sticky and slightly plastic; many very fine, common fine and common medium roots; abrupt and smooth transition to:

B1t 15 - 60 cm
dark reddish brown (2.5YR 3/4, moist); moderate, very fine angular blocky; common moderately thick cutans; few very fine and few fine pores; friable; slightly sticky and slightly plastic; very few very fine roots

B2t 60^{+} cm

Profile 3:

Ap 0 -15 cm
dark reddish brown (5YR 3/3, moist); moderately weak, very fine and fine subangular blocky; many very fine and common fine pores; very friable; slightly sticky and slightly plastic;very many very fine, common fine and few medium roots; abrupt and smooth transition to:

A1 15 - 30 cm
dark reddish brown (5YR 3/3, moist); moderate, very fine granular and fine subangular blocky; common very fine and common fine pores; friable; slightly sticky and slightly plastic; many very fine and few fine roots; clear and smooth transition to:

B1 30^{+} cm
moderate to strong, very fine angular blocky; abundant very fine, common fine and few medium pores in the upper part of the B1; friable to firm; slightly sticky and slightly plastic; root density strongly decreasing with depth.

Field 15	Local petrography: Wanjare granites	Soil: Tropudult	Date: 14-03-1979

A 0- 20 cm
dark reddish brown (5YR 3/3, moist); weak, very fine subangular and angular blocky; very fine, few fine, few medium and few coarse pores; very friable; non sticky and non plastic; very many very fine, few fine and few

medium roots; several termites holes; clear and wavy transition to:
B21t 20 - 45 cm
dark reddish brown (5YR 3/3, moist); moderate, very fine angular blocky; discontinuous cutans; many very fine, many fine, few medium and few coarse pores; very friable; non sticky and non plastic; many very fine, many fine and few medium roots; several termites holes; diffuse and smooth transition to:
B22t 45 - 120 cm
yellowish red (5YR 4/6, moist); weak, very fine subangular and angular blocky; continuous cutans; many very fine, common fine, few medium and few coarse pores; very friable; non sticky and non plastic; common very fine, common fine, few medium and few coarse pores; many termites holes; transition to rotton rock.
R 95 to 130 cm

Field 12	Local petrography: rhyolites	Soil: typic Paleudoll	Date: 12-04-1979

A 0 - 20 cm
dark reddish to reddish brown (5YR 3.5/4, moist); moderately strong, very fine and fine granular and very fine subangular blocky; very many very fine, common fine and few medium pores; very friable to friable; slightly sticky and slightly plastic; very many very fine, common fine and few medium roots; abrupt and smooth transition to:
B1t 20 - 30 cm
reddish brown (5YR 4/4, moist); strong, very fine angular blocky (few fine granular and few very fine subangular blocky); continuous cutans; very many very fine, common fine and few medium pores; friable; slightly sticky and slightly plastic; many very fine, few fine and few medium roots; diffuse and smooth transition to:
B21t 30 - 80 cm
reddish brown to yellowish red (5YR 4/5, moist); moderately strong, very fine angular blocky; continuous cutans; very many very fine, few to common fine, few medium and few coarse pores; firm; slightly sticky and slightly plastic; common very fine and few fine roots; several large biopores of groundvoles filled with very fine granular A-material and intact termite holes (ø up till 20 cm); diffuse and smooth transition to:
B22t 80 - 130$^+$ cm
reddish brown (2.5YR 4/4, moist); moderately strong, very fine angular and subangular blocky; continuous cutans; very many very fine and few fine pores; firm; slightly sticky and slightly plastic; few very fine roots; large biopores filled with very fine granulars.
R 175 to 350 cm

Field 13	Local petrography: rhyolites	Soil: oxic Argiudoll	Date: 08-03-1979

A1 0 - 25 cm
dark brown (7.5YR 3/2, moist); moderate, very fine subangular blocky; many very fine, common fine and few medium pores; friable; slightly sticky and slightly plastic; very many very fine, common fine and common medium roots; gradual and smooth transition to:
A3 25 - 50 cm
dark reddish brown (5YR 3/4, moist); moderate, very fine subangular blocky; many very fine, common fine, few medium and few coarse pores; friable; slightly sticky and slightly plastic; many very fine, few fine and common medium roots; gradual and smooth transition to:
B 50 - 90 cm
dark reddish brown (5YR 3/4), moist; moderately strong, very fine and fine subangular blocky; many very fine, many fine, few medium and few coarse pores; friable; slightly sticky and slightly plastic; common very fine roots; diffuse and smooth transition to:
C 90 - 140$^+$ cm
dark reddish brown (5YR 3/3, moist) with many black friable concretes; moderate, very fine subangular blocky; common very fine, few fine, very few medium and very few coarse pores; very friable, moderate sticky and

slightly plastic; few very fine roots.
R 135 to 200 cm

Field 3	Local petrography: basalts	Soil: typic Paleudoll	Date: 19-02-1979

Ap 0 - 22 cm
dark reddish brown (5YR 3/3, moist) moderate, very fine subangular blocky; many fine and many medium pores; very friable; slightly sticky and slighty plastic; many roots; abrupt and smooth transition to:
A1 22 - 85 cm
dark reddish brown (5YR 3/3, moist) moderate very fine subangular blocky; many fine and many medium pores; friable; slightly sticky and slightly plastic; many roots, several large biopores of groundvoles; gradual and undulating transition to:
B 85 - 130^{+} cm
dark red (2.5YR 3/6, moist); moderately strong, very fine to fine angular blocky; cutans; few fine and few medium pores; firm; slightly sticky and slightly plastic; few roots.
R 200 cm

Field 8	Local petrography: basalts	Soil: typic paleudoll	Date: 02-04-1979

A 0 - 25 cm
dark reddish brown (5YR 3/2, moist); strong, very fine granular and, moderate, very fine subangular blocky; many very fine and common fine pores; friable; very many very fine, many fine, few medium roots; clear and *smooth transition to:*
B1t 25 - 85 cm
dark reddish brown (5YR 3/3, moist); strong, fine angular blocky; moderately thick continuous cutans; very many very fine, common fine, few medium and few coarse pores; friable; many very fine and few fine roots; several groundvole holes; gradual and smooth transition to:
B2t 85^{+} cm
dark red (2.5YR 3/6, moist); strong, fine angular blocky; moderately thick continuous cutans; many very fine, common fine and few medium pores; firm; common very fine roots.
R > 320 cm

Field 2	Local petrography: felsites-andesites	Soil: typic Paleudoll	Date: 10-04-1979

Ap 0 - 20 cm
reddish brown (5YR 4/3, moist); moderately weak, fine granular and fine subangular blocky; very many fine, common fine and few medium pores; very friable to loose; slightly sticky and slightly plastic; very many fine, common fine and few medium roots; clear and smooth transition to:
A3 20 - 45 cm
reddish brown (5YR 4/3, moist); moderate, very fine and fine subangular and angular blocky; very many very fine, common fine and few medium pores; friable; slightly sticky and slightly plastic; many very fine, common fine and few medium roots; gradual and wavy transition to:
Bt 45 - 140^{+} cm
reddish brown (5YR 4/4, moist); moderately strong, very fine angular blocky; many discontinuous cutans; very many very fine and common fine pores; friable; slightly sticky and slightly plastic; many common very fine and common fine roots; several large biopores of groundvoles and termites till a depth of about 100 cm, (⌀ 2 - 8 cm), fillled with A-material; friable to firm black concretes (⌀ 1- 3 mm) density increasing with depth from 1 to 10 per 100 cm^2.

R >320 cm

Field 7	Local petrography: felsites-andesites	Soil: Typic Paleudoll	Date: 01-03-1979

A 0 - 50 cm
dark grayish brown (10YR 3/2, moist); moderate, fine granular; few fine and many medium pores; friable; slightly sticky and slightly plastic; many fine and medium roots; gradual and broken transition to:
B1 50 - 80 cm
dark reddish brown (5YR 3/3); moderate, very fine to fine subangular blocky; few fine and few medium pores; friable; slightly sticky and slightly plastic; many fine roots; gradual and wavy transition to:
B2 80 - 130 cm
dark reddish brown (5YR 3/4, moist); moderately strong, fine subangular blocky; few fine and few medium pores; firm; slightly sticky and slightly plastic; few fine roots; few termite chambers and groundvole holes filled with A-material.
R >320 cm

Field 10	Local petrography: volcanic ashes	Soil: pachic andeptic Hapludoll	Date: 02-03-1979

Ap 0 - 25 cm
black (10YR 2/1, moist); strong, very fine granular; many pores; very friable; non sticky and non plastic; many roots; abrupt and smooth transition to:
A1 25 - 50 cm
very dark grayish brown (10YR 3/2, moist); strong, very fine subangular blocky; many fine, few common and few coarse pores; friable; non sticky and non plastic; many fine roots, several large biopores of groundvoles filled with Ap- material; gradual and smooth transition to:
C 50 - 160 cm
dark reddish brown (5YR 3/4, moist); moderate, very fine subangular blocky; many fine and many common pores; very friable; slightly plastic and slightly plastic; many fine roots; several large biopores of goundvoles filled with A and C-material.
R 170 to 190 cm

Field 11	Local petrography: volcanic ashes	Soil: pachic andeptic Hapludoll	Date: 28-03-1979

Ap 0- 20 cm
very dark gray (10YR 3/1, moist); moderate, fine angular blocky; many very fine, common fine, few medium and few coarse pores; very friable; slightly sticky and slightly plastic; very many very fine, common fine and few medium roots; abrupt and smooth transition to:
A1 20 - 45 cm
very dark gray to very dark grayish brown (10YR 3/1.5, moist); moderate, very fine subangular and angular blocky; very many very fine, common fine, few medium and few coarse pores; very friable; slightly sticky and slightly plastic; many very fine and few fine roots; diffuse and smooth transition to:
B1t 45 - 70 cm
dark brown (7.5YR 3/3, moist); moderate to strong, very fine subangular blocky; discontinuos cutans (5YR 3/2); very many very fine, common fine, few medium and few coarse pores; friable; slightly sticky and slightly plastic; many very fine and few fine roots; large biopores of groundvoles filled with A-material; water-logging started from 60 cm; diffuse and smooth transition to:
B2t 70 - 150 cm
brownish yellow (10YR 6/8) with common firm black concretes; strong very fine and fine angular blocky; many

discontinuous cutans (5YR 3/1 to 4/6); abundant very fine, many fine, common medium and few coarse pores; firm; slightly sticky and slightly plastic; common very fine and few fine roots; large biopores of groundvoles filled with A-material; diffuse and wavy transition to:

B3 150+ cm

pale brown to yellow (10 YR 7/5, moist) with many (50 %) extremely firm black concretes; strong, very fine and fine angular blocky; abundant very fine, common fine, few medium and few coarse pores; firm.

Appendix 9. Chemical reactions and stability constants.

							Log K°	ref
Dissolution								
Goethite	↔	Fe^{3+}	+	$3OH^-$			- 44.0	1
Strengite	↔	Fe^{3+}	+	$H_2PO_4^-$	+	$2OH^-$	- 36.0	2
Brushite	↔	Ca^{2+}	+	HPO_4^{2-}	+	$2H_2O$	- 6.56	1
$Ca_3(PO_4)_2$	↔	$3Ca^{2+}$	+	$2PO_4^{3-}$			- 26.00	1
$Ca_4H(PO_4)_3.3H_2O$	↔	$4Ca^{2+}$	+	H^+ + $3PO_4^{3-}$	+	$3H_2O$	- 46.91	1
$Ca_{10}(PO_4)_6(OH)_2$	↔	$10Ca^{2+}$	+	$6PO_4^{3-}$	+	$2OH^-$	- 113.70	3
Fluorapatite	↔	$10Ca^{2+}$	+	$6PO_4^{3-}$	+	$2F^-$	- 120.86	1
Gibbsite	↔	Al^{3+}	+	$3OH^-$			- 33.8	2
Variscite	↔	Al^{3+}	+	$H_2PO_4^-$	+	$2OH^-$	- 30.50	1
Kaolinite	↔	$2Al^{3+}$	+	$2H_4SiO_4^{\circ}$	+	$6OH^-$	- 76.37	4
Calcite	↔	Ca^{2+}	+	CO_3^{2-}			- 8.35	1
Carbon dioxide	↔	H_2CO_3					- 1.46	1

							Log K°	ref
Hydrolyses								
Fe^{3+}	+	H_2O	↔	$Fe(OH)^{2+}$	+	H^+	- 2.4	1
Fe^{3+}	+	$2H_2O$	↔	$Fe(OH)_2^+$	+	$2H^+$	- 6.9	1
Fe^{3+}	+	$3H_2O$	↔	$Fe(OH)_3^{\circ}$	+	$3H^+$	- 13.6	1
Fe^{3+}	+	$4H_2O$	↔	$Fe(OH)_4^-$	+	$4H^+$	- 22.8	1
Al^{3+}	+	H_2O	↔	$Al(OH)_2^+$	+	H^+	- 5.02	1
Al^{3+}	+	$4H_2O$	↔	$Al(OH)_4^-$	+	$4H^+$	- 23.57	1

					Log K°	ref
Protolyses						
H_3PO_4	↔	H^+	+	$H_2PO_4^-$	- 2.12	1
$H_2PO_4^-$	↔	H^+	+	HPO_4^{2-}	- 7.22	2
HPO_4^{2-}	↔	H^+	+	PO_4^{3-}	- 12.33	1
H_2CO_3	↔	H^+	+	HCO_3^-	- 6.35	1
HCO_3^-	↔	H^+	+	CO_3^{2-}	- 10.33	1
H_2O	↔	H^+	+	OH^-	- 14.0	1

					Log K°	ref
Complex formation						
Ca^{2+}	+	HPO_4^{2-}	↔	$CaHPO_4^{\circ}$	2.70	1
Ca^{2+}	+	$H_2PO_4^-$	↔	$CaH_2PO_4^+$	1.08	1
Ca^{2+}	+	CO_3^{2-}	↔	$CaCO_3^{\circ}$	3.20	1
Ca^{2+}	+	HCO_3^-	↔	$CaHCO_3^+$	1.26	1

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Appendix 10a. Cumulative grain yield response (kg/ha) to repeated subseed placement of fertilizer P. (N was applied at constant rates, see Chapter 6.3.1)

	P: 11 kg/ha			P: 33 kg/ha		
	season 1	season 1+2	season 1+2+3	season 1	season 1+2	season 1+2+3
Granite 15	740	2658	5292	1942	4568	8701
Granite 6	1285	3370	6115	1116	3470	6163
Rhyolite 12	990	2666	5713	2679	5106	8261
Basalt 8	1581	3188	5063	2813	4484	7278
Felsite-andesite 2	1476	2008	3655	2326	3354	5321
Average	1214	2778	5168	2175	4196	7145

Appendix 10b. Cumulative financial net return (Ksh/ha) to repeated subseed placement. Calculations are based on 1990 prices (Smaling 1993): Maize 2.5 KSh/kg, P 50 KSh/kg, 30 Ksh = 1 US$.

	P: 11 kg/ha			P: 33 kg/ha		
	season 1	season 1+2	season 1+2+3	season 1	season 1+2	season 1+2+3
Granite 15	1300	5545	11580	3205	8120	16803
Granite 6	2663	7325	13638	1140	5375	10458
Rhyolite 12	1925	5565	12633	5048	9465	15703
Basalt 8	3403	6870	11008	5383	7910	13245
Felsite-andesite 2	3140	3920	7488	4165	5085	8353
Average	2486	5845	11269	3788	7191	12912

Appendix 10c. Cumulative grain yield response (kg/ha) to subseed placement of fertilizer P. (N was applied at constant rates see Chapter 6.3.1)

	P: 22 kg/ha			P: 44 kg/ha		
	season 1	season 1+2	season 1+2+3	season 1	season 1+2	season 1+2+3
Granite 15	1631	3333	4899	2156	4413	7735
Granite 6	1157	2372	3912	2302	5161	8263
Rhyolite 12	1438	2544	3515	2685	4106	5545
Basalt 8	2133	2761	3883	2835	4126	5885
Felsite-andesite 2	1534	2081	3132	1978	2671	3431
Average	1579	2618	3868	2391	4095	6172

Appendix 10d. Cumulative financial net return (Ksh/ha) to subseed placement. Calculations are based on 1990 prices (Smaling 1993): Maize 2.5 KSh/kg, P 50 KSh/kg, 30 Ksh = 1 US$.

	P: 22 kg/ha			P: 44 kg/ha		
	season 1	season 1+2	season 1+2+3	season 1	season 1+2	season 1+2+3
Granite 15	2978	7233	11148	3190	8833	17138
Granite 6	1793	4830	8680	3555	10703	18458
Rhyolite 12	2495	5260	7688	4513	8065	11663
Basalt 8	4233	5803	8608	4888	8115	12513
Felsite-andesite 2	2735	4103	6730	2745	4478	6378
Average	2847	5446	8571	3778	8039	13230

Curriculum Vitae

De auteur werd geboren op 5 maart 1949 te Hazerswoude. In 1966 behaalde hij zijn HBS-B diploma aan de Rijks HBS te Gouda. Hierna begon hij zijn studie in de bodemkunde en bemestingsleer aan de Landbouwuniversiteit te Wageningen. Tijdens zijn praktijktijd in 1971 en 1972 verrichte hij fosfaatbemestingsonderzoek in Brazilië, in de staat Paraná, bij het Instituto de Pesquisas Agropecuária Meridional (IPEAME) te Curitiba. Het onderzoek maakte deel uit van een samenwerkingsproject tussen de Braziliaanse en Duitse overheid. In januari 1976 studeerde hij af als Landbouwkundig ingenieur met als hoofdvakken bodemvruchtbaarheid en bodemverontreiniging en als bijvak natuurbehoud en natuurbeheer.

Na zijn studie kwam hij in dienst bij de Vakgroep Bodemkunde en Plantenvoeding, eerst in het kader van onderzoek naar geschiktheid van ion-specifieke elektroden voor analyses, en vanaf het najaar 1976 ten behoeve van het fosfaatonderzoek in Kenia. Dit onderzoek maakte deel uit van het multidisciplinaire bodemkundige trainingsproject van de landbouwuniversiteit Wageningen. Voor de voorbereiding en de uitvoering van het onderzoek verbleef hij in het najaar 1976 en van medio 1977 tot 1979 in Kisii in Kenia. Daarbij was hij tevens betrokken bij de training van studenten. Nadat het project in Kisii was beëindigd, werd het onderzoek voortgezet bij de Vakgroep Bodemkunde en Plantenvoeding. De resultaten van dit onderzoek zijn verwerkt in dit proefschrift.

In februari 1982 trad hij in dienst bij het Openbaar Lichaam Rijnmond voor het opzetten en coördineren van het bodemsaneringsprogramma in het Rijnmondgebied. Sinds de opheffing van deze organisatie in 1986 is hij werkzaam bij de provincie Zuid Holland, eerst als hoofd van het bureau voor de uitvoering van bodemsaneringsprojecten in de Regio Zuid-Oost en daarna als stafmedewerker en beleidscoördinator voor de ontwikkeling en afstemming van het milieubeleid met name op de onderdelen bodemsanering, bodembescherming en afval. In het kader daarvan was hij betrokken bij ondermeer de ontwikkeling van het beleid met betrekking tot bodemsanering, baggerspecie, zuiveringsslib, voormalige stortplaatsen, de ontwikkeling van bodemonderzoeksstrategieën, de afstemming tussen bodemsanering en ruimtelijke ordening, milieueffectrapportages, milieubeleidsplanning, strategieontwikkeling van de Dienst Water en Milieu, alsmede bij de internationale milieusamenwerking tussen de provincie Zuid-Holland en Tsjechië (Noord Bohemen).

In 1994 nam hij het initiatief voor de ontwikkeling van een alternatief voor het omstreden "Bentwoud", één van de strategische groenprojecten van het Structuurschema Groene Ruimte. Dit alternatief is als "Bentveldplan" door het Platform Bentveld in samenwerking met de streek ontwikkeld en in de discussie over de inrichting van dit deel van het Groene Hart gebracht.