MONITORING PHOSPHORUS NUTRITION OF MAIZE ON FOUR LANDFORM TECHNOLOGIES IN THE VERTISOLS OF THE ACCRA PLAINS

BY

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A THESIS SUBMITTED TO THE DEPARTMENT

OF SOIL SCIENCE, UNIVERSITY OF GHANA,

IN PARTIAL FULFILMENT OF THE REQUIREMENT

FOR THE MASTER OF PHILOSOPHY (M.Phil.)

DEGREE IN SOIL SCIENCE

APRIL, 1997.

DEDICATION

Dedicated to the Glory of God Almighty and to my Parents.

DECLARATION

I hereby declare that the work presented in this thesis was carried out by myself and has never in part or in whole been presented to any other University for the award of a degree.

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ACKNOWLEDGEMENTS

I wish to express my sincere gratitude to my supervisor, Prof. Yaw Ahenkorah, for his invaluable comments, suggestions, and guidance throughout all the stages of this work. Many thanks go to all the lecturers, Department of Soil Science, for their encouragement and preparedness to help whenever necessary. I am especially grateful to Dr. G. N. N. Dowuona, my co-supervisor, Department of Soil Science, and Dr. I. K. Ofori, Department of Crop Science, for their comments and encouragement. I also wish to express my gratitude to Dr. J. W. Oteng, Agricultural Research Station, Kpong, for making land available for the trial. I am highly indebted to all the technicians, Department of Soil Science, for their assistance. And to all my classmates, I say thank you very much for your support and encouragement.

To my parents, sisters and brothers, thanks for your love.

Finally, may the Lord Almighty be praised for His protection, guidance and love. To Him, be Glory and Honour.

ABSTRACT

A field trial was started in August 1994, during the minor cropping season to investigate the efficiency of four Landforms in the production of maize with special emphasis in phosphorus (P) management in Vertisols at three localities in the Accra Plains of the Coastal Savanna zone of Ghana. The four Landforms were: Flat, Ridged, Ethiopian and Cambered beds.

Generally, the soils were low in available P. Raising available P levels in the soil by the addition of fertilizer led to significant increase in dry weight of maize in all the Landforms. On the Cambered bed, however, raising the fertilizer above 50 % of the recommended rate did not cause significant yield increase.

The Landforms had significant influence on P uptake and dry matter production. In all instances, the raised beds, i.e. Ridged (R), Ethiopian (EB) and Cambered (CB) significantly outperformed the Flat (F) bed in terms of P uptake and dry matter production. Among the raised beds, the Cambered bed had significantly higher dry matter yield than the Ridged and Ethiopian beds.

The relative agronomic efficiency (RAE) of the four landforms were in the order of CB > EB = R > F ($P < 0.05$). Unlike the Ridged and the Ethiopian beds, the RAE of the Cambered bed at 50 % fertilizer application was higher than the 100 % fertilizer application. Soil organic P formed about 25 % of the total P and this value did not change significantly throughout the growing season. Calcium bound phosphate (Ca-P) was the dominant inorganic P and constituted about 78 % of the active inorganic P in

the soils. Iron bound phosphate (Fe-P) was the least and constituted 2 % of the total active inorganic P. The two inorganic P fractions significantly correlated with P uptake and dry matter production. Though both Ca-P and Aluminium bound phosphate (Al-P) did not change significantly during the maize growing period, the Fe-P on the other hand reduced to about one-half its initial value. Generally, increase in fertilizer application increased P uptake, with the highest P uptake on the CB and least on the F. A significant Landform x fertilizer interaction was observed for dry matter production when 50 % fertilizer application on the CB out yielded 100 % fertilizer on the F. Generally, there was negative soil available P balance in all the Landforms and at all the rates of fertilizer application at the end of the season.

TABLE OF CONTENTS

CHAPTER THREE

CHAPTER FOUR

CHAPTER SIX

List of tables

LIST OF FIGURES

CHAPTER ONE

1 INTRODUCTION

Vertisols occupy about 280 million ha (about 2 %) of the world's land area and have been classified as Tropical Black Earth (FAO/UNESCO, 1990). Though they are not extensive in Ghana, they are considered important since they are one of the productive group of soils and are strategically located within the coastal and interior Savanna Zones of the country. They occupy a total area of about 1,630 sq. km in the Coastal savanna (Brammer, 1967) and Adu and Stobbs (1981) estimated 190 sq km for the Guinea savanna zone of the country.

Though Vertisols are among the most productive soils in the Sub-Saharan Africa, they are agriculturally under utilized within the traditional farming practices. The major constraints affecting increased farming activities on these soils include lack of technology for the conservation and the shedding of excess water, the effect of water logging during prolonged rains, serious soil tillage and nutrient management problems.

Various Landform technologies have been developed and employed elsewhere to promote both the drainage of excess water during the cropping season and the conservation of water in the minor season to ensure successful cultivation of crops. It is hoped that the continuous use of Vertisols of the Accra Plains should be possible if appropriate Landforms could be developed to provide drainage of excess water and conserve enough moisture for crop production.

Apart from the difficulty in tillage, sustainable and improved crop production depend on the provision of adequate plant nutrients. Available P has been found to be generally low in the Vertisols of the Accra Plains. There has, however, been little investigation on the chemical characterisation, relative distribution, the nature and behaviour of phosphorus in the Vertisols of Ghana. Work done elsewhere indicated that there is a marked response to P fertilisation but higher concentration reduces yields (Desta, 1982). The sustainability of soil fertility and productivity do not depend on the source of P, but the quantity applied (Wallingford, 1991).

The study was carried out to evaluate the efficiency of phosphorus uptake on four different Landform technologies for crop production, i.e. Flat, Ridged, Ethiopian and Cambered bed and different rates of fertilizer application using maize as the test crop.

The objectives of the study were:

1. To compare the relative efficiencies of the four Landforms using Relative Agronomic (RAE) efficiency at different rates of fertilizer.
2. To monitor P status of the Landforms.

About the same amount is distributed in more than 30 African countries (FAO, 1986). Other countries in the sub-saharan Africa with Vertisols exceeding one million hectares are: Tanzania, 5.6; Botswana, 4.9; Namibia, 4.1; Kenya and Zambia, 2.6 each; Zimbabwe, 2.3; Mozambique, 2.0; Somalia, 1.8; Burkina Faso and Nigeria, 1.3 each and Cameroon, 1.2 million hectares.

Vertisols in Ghana are almost entirely confined to the Coastal and Interior Savanna Zones. They occupy approximately 2.5 % of the total land area of Ghana. (Acquaye and Owusu Bennoah, 1989). Brash (1962) and Brammer (1967) estimated the total Vertisol coverage of the Coastal Zone to be 1630 sq km and Adu and Stobb (1981) estimated the total Vertisols coverage of the Guinea savanna zone of Ghana to be 190 sq km. From these estimates the total coverage of Vertisols in Ghana is approximately 1830 sq km.

The Vertisols of Ghana occur under low rainfall (900 - 1400 mm) spread over two rainy seasons in the south and over one extended rainy season in the north (Acquaye and Owusu-Bennoah, 1989). The Akuse association comprises Akuse, Lupu, Ashaiman, Bumbi series and the Prampram subseries (Brammer, 1967). They are developed over the basic gneisses. The Vertisols of the coastal savanna generally occur in a very gently undulating land with an elevation range from zero to about 50 m above sea level. According to Adu (1985), the general slope of the land on which they occur is about 1 - 2 %, rarely exceeding 5 % and they usually occupy the whole topography from low-lying summits to valley bottoms, isolated inselbergs rise abruptly from the plains to as high as 420 m.

2.3 Farming on Vertisols

According to Ahmad (1984), graminaceous crops i.e. cereals, sugar cane and pasture grasses are best suited for these soils. Root systems are extensive so crops can better withstand damage due to soil cracking. The length of the growing period on Vertisols may range from less than 90 days to over 300 days (Srivastava, 1992).

The Vertisols of the Coastal Savanna have been cropped by local farmers for centuries with very little input (Acquaye and Owusu-Bennoah, 1989). According to Owusu-Bennoah and Dua-Yentumi (1989), about 14 crops are grown on these soils. The main crops are maize (*Zea mays*), rice (*Oryza sativa*), sugar cane (*Saccharum officinarum*) and cassava (*Manihot utilissima*), whilst the minor crops are vegetables, mainly pepper (*Capsicum annuum*), okra (*Hibiscus esculentus*), garden eggs (*Solanum melongena*), tomatoes (*Lycopesicum esculentum*). The crops are generally planted with the first rains from mid-March to early April and late cropping of maize and cassava is carried out during the second rainy season in August/September.

2.4 Land preparation

Physical conditions of Vertisols indicate that these dark cracking clays are virtually self loosening because they consist of montmorillonite, the expanding-lattice clay mineral, which causes them to expand when wet and contract when dry. They also observed that since crop root development is not impeded in these soils, deep soil loosening is not necessary and that the primary purpose of seed bed preparation is for the effective control of weeds.

by stickiness when wet and hardness when dry. He further stated that Vertisols by their nature limit the growth of roots, which in turn inhibits the ability of root systems to absorb nutrients and water. Therefore, concentration in the more fertile top soil on which the crop is planted is regarded as a technique in fertility maintenance. Not only is the surface soil more fertile, but also it is the part of the profile in which the soil would resist ped disruption on wetting due to higher organic matter content.

According to Owusu-Bennoah and Dua-Yentumi (1989), initial clearing of vegetation is done with cutlass, followed by burning. A hoe is then used to break the tussocks of the grass. Planting of crops is done entirely on Flat land. They further stated that since Ghanaian Vertisols are found on slopes ranging from 1-2 %, the rainy season results in many prepared lands being flooded giving rise to stunted growth of maize and other crops.

Various management technologies employ different land shaping arrangements to promote drainage of excess water from the soils to ensure successful cultivation of crops. Some of these management technologies have been developed on similar soils elsewhere (Kanwar and Virmani, 1987; Jutzi and Abebe, 1987).

It is hoped that, continuous use of Vertisols for sequential cropping is possible if an appropriate Landform could be developed to drain excess water in both the major and minor rainy seasons and also to ensure storage of water for crop growth.

In most of the tropics, the indigenous farmer uses ridge cultivation. The basic reason for ridging is to overcome some constraints which hamper the adoption of complete tillage. Kowal and Stockinger (1973) listed some of the advantages of ridged cropping as follows:

i) top soils enriched with ashes and plant residues are concentrated in the area of plant roots,

ii) ridges can protect against soil erosion when used on the contours of slopes, and

iii) during wet periods, aeration for roots of crops planted on top of the ridge is improved while the furrows act as open drains.

Sato *et al*. (1968) observed that maize plant grown on ridges produced heavy tops while root growth was greater on unridged plots. Their work also revealed that the N, P and K content of plants from both ridged and unridged plots were similar. Hulugalle (1989) reported that tied-ridging significantly increased the grain and dry matter production of maize in the Sudan savanna belt of Burkina Faso. In the sub-humid zone of Nigeria, planting sorghum on ridges gave a 60 % higher grain yield than planting on the flat (Mohamed et al.,1987). It was reported by Webster and Wilson (1980) that the effect of ridges on yield was found to be variable but the tendency was for ridges to be beneficial on light soils in drier areas. According to Mitchell (1987), generally, water conservation treatment as contour bunding and tired-ridging reduce runoff and increase moisture status in the soil profile, it reduces crop yield by causing water logging. Dua-Yentumi et al. (1992), reporting on Vertisols of Accra plains of Ghana stated that the modified Cambered beds had the highest maize growth at maturity followed by the Ridged bed with the Flat bed lagging behind. This trend was also observed with grain yield. Their report indicated that Cambered beds gave the highest yield.

2.5 Fertilizer use

According to Ahmad (1989), there are large areas of Vertisols, especially in Africa, where fertilizer is not used and some fertility maintenance is achieved through cultural means. He reported that there is no significant positive response to fertilizer if water is lacking. This is probably indirectly responsible for the non use of fertilizer in many rainfed systems. In contrast, in irrigated systems, significant crop responses to fertilizer is often obtained (Abdulla, 1989). Among the major constraints affecting increased farming activities of these soils is nutrient management (Acquaye and Owusu Bennoah, 1989). Because of these problems, indigenous farmers prefer to restrict their cultivation to small areas and on lighter soil and often leave large track of Vertisols for rough grazing.

2.6 Nutrient status of Vertisols

Soils of West Africa savanna are generally low in available P and this is the most limiting nutrient factor in crop production in this region (Jones and Wild, 1975). This limitation has been reported in Burkina Faso by Jenny (1965).

Among the three major plant nutrients in the soil, nitrogen level can be improved by fixation of atmospheric nitrogen by legumes. The potassium status is usually high enough in the West Africa savanna soils to maintain long periods of continuous cultivation. It is only P whose status in the soil has been shown to be low, and need to be added to the soil through the use of inorganic phosphorus fertilizer.

Vertisols are generally fertile soils, but poor drainage and difficult workability limit nutrient availability. There is, therefore, a great deal yet to be learnt about soil fertility management of Vertisols (Ahmad, 1989).

2.7 Phosphorus

2.7.1 Importance of phosphorus in agriculture

Plant tissue contains about 0.004 % of phosphorus as deoxyribonucleic acid (DNA), 0.04 % phosphorus as ribonucleic acid (RNA) and 0.03 % phosphorus as lipids (Bieleski, 1973). Phosphorus has a genetic role through ribonucleic acid and also functions in energy transfer through adenosine triphosphate (ATP). Phosphorus is, therefore, indispensable to all forms of life. In plant, the function of phosphorus include cell division, root and seed development, crop maturation, crop quality and resistance to diseases. According to Ozanne and Asher (1965), P deficiency may reduce seed numbers and seed size. Ardeeva and Andreeva (1974) observed that phosphorus deficiency reduced the rate of photosynthesis more severely in plants with C-4 photosynthetic pathway (i.e. maize) than in those with C-3 pathway (i.e. beans). Brock (1973) reported that an increase in the amount of N fixed by soybeans was observed with an addition of phosphorus.

Apatite in rocks is the ultimate source from which P is derived. Although the total P content in the soil is not a good indicator of crop response, low values suggest its deficiency in soils. The phosphorus status of soil is one of the most important factors that control the response of a crop to added phosphate. The phosphorus status of Vertisols is highly variable, and it seems related to the origin of the soil. In the Carribeans, Vertisols derived from response of a crop to added phosphate. The phosphorus status of Vertisols is highly variable, and it seems related to the origin of the soil. In the Carribeans, Vertisols derived from calcareous materials have very satisfactory levels of total and available P (Ahmad and Jones, 1969a), and in cases of those derived from volcanic materials there is the problem of availability.

Deficiency of phosphorus is widespread in Vertisols (Swindale, 1982). Next to nitrogen, phosphorus is the most limiting nutrient in Vertisols (Finck and Venkateswarlu, 1982). It is believed that Vertisols of basaltic origin are less prone to deficiency than those developed in granites and sedimentary rocks (Singh and Venkateswarlu, 1985). With phosphorus the problem is more of unavailability than of total quantity present in the soil (Dudal, 1965; Hubble, 1984).

Total phosphorus in the Vertisols of Ghana has been reported to range between 150 - 298 mg/kg (Acquaye and Owusu-Bennoah, 1989). Bouyer and Damour (1964) reported 149 - 227 mg/kg total P for Vertisols in Togo and Cameroon. According to Jones and Wild (1975), the high total P in the Vertisols may reflect the influence of the high clay content, which gives a high capacity for holding phosphate against leaching.

2.7.2 Available phosphorus

Phosphorus availability in Vertisols is largely assessed by the alkaline bicarbonate extraction method (Olsen et al.,1954). Some Vertisols contain as low as 1 mg/kg (Katyal, 1978) with a general range of 2-10 mg/kg for some Indian Vertisols. In India, a soil is considered deficient if it contains less than 5 mg/kg Olsen-extractable P (Tandon and Kanwar, 1984). According to Kanwar and Rego (1983), the critical lower limit of water-soluble P for a soil to P application was 0.5 mg/kg. Katyal and Venkatramaya (1983) reported that phosphorus availability fluctuated with season. Its availability was suppressed by cold temperature of the post rainy season. Similarly, post rainy crops depend largely on the fertilizer available phosphorus (Kanwar et al.,1973). The Vertisols of Ghana have low available P ranging from 0.1-3.5 ppm with an average of 1.6 ppm since they are derived from hornblende gneiss which contains very small amount of apatite (Acquaye and Owusu-Bennoah, 1989).

2.7.3 Organic phosphorus

Soils furnish P to plant from both organic and inorganic forms (Magistad, 1941). The organic P may be several times greater than the soluble inorganic phosphate. Pierre and Parker (1927), however, found it to be a poor source for maize, soybean and buckwheat.

The rate at which P becomes available from the organic fraction depends largely on conditions favourable for organic matter decomposition. Abbott and Lingle (1968) confirmed P-solubilizing processes, including mineralization of organic P in soil and amendments, over a period of eight weeks during which soil temperature increased from 15 to 20 °C. Eid *et al.* (1951) found that for crops grown at high soil temperatures the accuracy of chemical soil test for P availability may be improved by measuring and using inorganic P and the appropriate organic P fraction. Moreover, the soil organic P that mineralized during the growth of a crop may contribute to the needs of crops. Black and Goring (1953) reported a positive relationship between organic P and organic matter. The organic carbon : organic P ratio is an index of the mineralization capacity of the organic P. Under tropical conditions, organic P is readily in the range of 49 - 69 mg/kg, constituting between 21 to 40 % of the total P in the Vertisols of Ghana.

2.7.4 Active inorganic phosphorus forms

The status of available phosphorus in soils is normally related to the different active inorganic phosphorus forms viz; iron-phosphate (Fe-P), aluminium-phosphate (Al-P) and calcium-phosphate (Ca-P). Halm and Bampoe-Addo (1972) observed that different fractions or part of the different fractions of soil phosphorus are removed by various soil test methods used in Ghana. They also stated that little is known about the relationship between available phosphorus and the various inorganic phosphate fractions and their contribution to the labile pool in some Ghanaian soils.

The Bray and Olsen methods were highly correlated with aluminium phosphate (AL-P) but not with calcium phosphate (Ca-P) (Chai and Cardwell, 1959; Pratt and Garder, 1964). Grigg (1965) observed that the Bray and Olsen extractants removed mainly Al-P and not significant amount of iron phosphate (Fe-P). Studies done on fifteen Ethiopian soils showed that the distribution of active P forms was in the order of Fe-P > Ca-P > Al-P (Desta,1982). Viswanatha and Doddamani (1991) reported that the distribution of Al-P, Fe-P, reductant-soluble-P, occluded-P and Ca-P did not follow a definite pattern along the profile. The Ca-P was, however, found to be the dominant form of P; about 18.3 % of the total P in some Vertisols of Karnataka, India. Data obtained by researchers at ICRISAT (1984) showed that in a Vertisol from Andhra Pradesh, (India), about two-thirds of the phosphate was associated with calcium and about one-third with iron and there was little Al-P.

Acquaye and Owusu-Bennoah (1989) reported that most of the inorganic phosphate was tied up with Ca rather than with Al or Fe in the Vertisols of Ghana. According to Finck and Venkateswarlu (1982), because Ca is the dominant cation in the exchange complex of the Vertisols, added P is usually transferred as calcium phosphate. The only Fe-P mineral that has been found in crystals which are recognisable is vivianite ($Fe_3(P0_4)_2$-$8H_20$), a ferrous phosphate that is often found in water logged or poorly drained soils (Russell, 1973). Lindsay and Stephenson (1959) have shown that when granulated super phosphate is added to a soil, taranakite, ($H_6K_3Al_5(PO_4)_8.18H_20$ and $H_8K(Al.Fe)_3(PO_4)_6.6H_20$) may be formed. In well drained soils one of the principal Al-P that has been recognized belongs to plumbogummite group of minerals with a general formula : $M.Al_3(PO_4)_2(OH)5H_2O$ where M is usually barium, strontium, yttrium or cesium (Russell, 1973). Calcium phosphate exists in several forms. The most important ones are:

$Ca(H_2PO_4)_2.H_2O$	Monocalcium phosphate
$CaHPO_4.2H_20$	Dicalcium phosphate
$Ca8H_2(PO_4)_6.5H_20$	Octacalcium phosphate (Brown Smith *et al.*, 1954)
$Ca3(PO_4)_2$	Tricalcium phosphate (Sample *et al.*, 1980)
$Ca10\ (PO_4)_6\ F_2$	Fluorapatite.

The abundance of Fe-P in the poorly drained surface sample is supported by the general fact that under flood conditions, Fe-P more than other fractions is the source of available phosphorus (Russell, 1973).

2.8 Potassium

The K status of vertisols of the humid tropics is usually quite good if they are derived from sediments and especially if they have previous marine history (Ahmad *et al.*, 1962). Vertisols are high in total K (about 1 %) and exchangeable K (40-50 mg/kg) (Finck and Venkateswarlu, 1982). Potassium has been found to be very high in Ghanaian soils, the amount depends on the nature of the parent materials.

Acquaye (1973), noted that soils derived from basic rocks, including Vertisols tended to have a high K fixation, a property also reflected by their high buffering capacity. Said (1971) showed that drying the Gezira Vertisol increased exchangeable potassium and

Table 2.1. Range of exchangeable K in Vertisols of some countries.

Country	K range(mg/kg soil)	Reference
Ghana	0.2-0.3	Oteng (1974) Brammer and Endredy (1954).
Ghana	0.2-0.5	Acquaye (1973)
India	0.5-1.3	Kalblade and Swamyriatha (1976)
Sudan	0.6-1.6	Abdulla (1985)
Australia	0.7-2.3	Northcote (1984)

the effect was greater as intensity of drying increased. In the Carribean, some of these soils which are derived from relatively calcareous materials may have low levels of K (Ahmad and Jones, 1969b), but it is not known how widespread this situation is. According to Ahmad and Davies (1970), levels of exchangeable K and K saturation would have to be fairly much higher than required for adequate plant uptake for appreciable fixation to occur. In some of the soils, plants may experience difficulty in obtaining adequate supplies of K, not due entirely to low levels, but partly also because of an adverse balance of exchangeable Ca, Mg and K (Ahmad and Jones, 1969b). According to Katyal et al. (1987), benefits from K fertilisation have seldom been distinct in the semi-arid Tropics.

2.9 Nitrogen

The most universally deficient nutrient in tropical Vertisols is N (Katyal *et al.,* 1987), and its judicious use can be an important means of increasing productivity. Dudal (1965) also reported similar N levels in Indian Vertisols which was less than 0.1 %. Syrian Vertisols had an average of 0.06 % N (ICARDA, 1981), but Australian and North American Vertisols had greater than 0.1 % N (Williams and Colwell, 1977). Ayoub (1986) reported a range of 0.02 and 0.06 % for Sudan Gezira Vertisols.

The total N in the Vertisols of Accra plains ranged between 0.07 and 0.13 % with an average of 0.09 % (Acquaye and Owusu-Bennoah 1989), and according to Oteng (1980), the annual production of mineral N is usually not sufficient for more than very modest yields. Nitrogen fixation by symbiotic association of legumes and non-legumes with rhizobia contributes about 15-20 kg N/ha (Dancette and Poulain, 1968).

2.10 Organic matter

Organic matter is the main source of nitrogen in the soil. It's readily mineralizable fraction measured by alkaline KMn04 extraction provides an index of N availability over the life of a crop (Subbiah and Asija, 1956). The organic matter content of Vertisols in Ghana is low, with the mean organic carbon content of 1.1 % (Acquaye and Owusu Bennoah, 1989). However Brammer and de Endredy (1954) reported a range of 0.5 - 4.0 % for Ghana Vertisols.

A range of 2.0-6.0 % has been reported for Australian and North American Vertisols (Dudal and Bramao, 1965). Landsay et al. (1982) and ICRISAT (1984) reported a range of 0.3 - 0.9 % for Indian Vertisols. Robinson et al. (1970) reported values greater than 0.5 % for the Gezira Vertisols of Sudan. The low organic carbon content may be attributed to the low rate of addition of organic residues from the savanna vegetation (Sanchez, 1976) and the annual burning of the grasses by herdsmen as a means of regeneration of fresh grasses (Greenland and Nye, 1959).

The dark colour of Vertisols, despite the low content of organic matter, is caused by complexes of it with the smectite clay, probably with some contribution by sorption of Fe, Mn, Ca and Mg (Singh, 1956). Generally, small organic carbon content and large C:N ratio cause nitrogen deficiency in most Vertisols. The wide range in C:N ratio is attributed to the high nitrification rate and the losses of N, as the Ca and moisture status are very favourable to increase microbial activity. The loss of N might also be caused by denitrification resulting from poor drainage.

2.11 Exchangeable bases

Calcium and Magnesium constitute the dominant bases in the Vertisols of Ghana (Acquaye and Owusu-Bennoah, 1989). It was reported that the contents of soil exchangeable calcium and magnesium in the top soil ranged between 16.6 and 20.5 cmol(+)/kg and 7.3 13.0 cmol(+)/kg respectively. It was also observed in the Ghanaian Vertisols that exchangeable calcium was generally higher than magnesium and the mean ratio of Ca:Mg of the soil is 2:1 (Acquaye and Owusu-Bennoah,1989).

Similar results were obtained by Debele (1983) for Ethiopia Vertisols, Mowo (1987) for Tanzania Vertisols and Van de Weg (1987) for Kenya and Sudan. Mowo (1987) reported 0.49 cmol(+)/kg of exchangeable sodium for the surface soil (0-30 cm) in Tanzania. A range of 0.5 to 1.2 cmol(+)/kg with a mean value of 0.7 cmol(+)/kg exchangeable sodium was reported for Vertisols of Ghana (Acquaye and Owusu-Bennoah, 1989). Robinson *et al.* (1970) reported that a satisfactory exchangeable sodium percentage (ESP) in the Gezira Vertisol is between 6 and 25 mg/kg with optimum of about 10 mg/kg soil. The importance of ESP is largely physical.

The CEC of Vertisols is commonly in the range of 30 - 60 cmol(+)/kg of soil (Jewitt,1955; Landsey *et al.,* 1982; Ahmad, 1983). According to Santanna (1989), Niger Vertisols have CEC of 60-80 cmol(+)/kg and the exchange complex is calcium saturated. For Ghanaian Vertisols, a range of 31-41 cmol(+)/kg has been reported by Acquaye and Owusu-Bennoah (1989). Sehal and Bhattacharjee (1987) reported mean values of 53.9 cmol(+)/kg and 42 cmol(+)/kg for Vertisols of India and Iraq respectively. Ethiopian Vertisols have CEC values ranging from 35 to 70 cmol(+)/kg soil (Jutzi and Abebe, 1987).

2.12 Clay mineralogy of Vertisols

Structure and consistency are generally a direct function of the ratio of clay to sand and the mineral composition of the clay. According to Santanna (1989), Vertisols generally have clay percentage ranging between 35 and 70 % or even more. Clay content of Ghanaian

Vertisols is between 40 - 60 %, that of Niger is between 30 - 50 % and the Cameroon varies from 30 - 80 % (Santanna, 1989). According to Stephen (1953), in the Athi plains of Kenya and the coastal area of Ghana the clay is largely montmorillonite in the Vertisols, whereas in Togo aluminous beidellite occurs (Konnetsron et al., 1977).

2.13 Soil pH

The Vertisols of Ghana generally have a nearly neutral surface pH in 0.01 M $CaCl_2$ (Brammer, 1967). Acquaye and Owusu-Bennoah (1989) reported a pH range of 6.5 to 7.4. with a mean value of 7.0. According to Bunting and Lea (1962) and Robinson et al. (1970), the mean pH value of Sudan Vertisols is between 8.0 - 9.5. The mean pH for the Vertisol in India ranges from 7.2 to 8.5 (ICRISAT,1984) and the Vertisols in Iraq have a mean of 7.9 (Sehal and Bhattacharjee, 1987). Ahmad (1983) reported the occurrence of acid Vertislos with a pH of 5.0 - 6.2 in the Carribean area. According to Ahmad (1984), Vertisols may have pH as low as 4.0, but do not necessarily have aluminium toxicity problems as do other soils with such low pH. This difference could be due to the fact that Vertisols are derived from both acid and basic parent materials. According to Fullerton et al. (1988), the ammonification of urea occurs rapidly, but the resulting NH3 - N does not increase the pH of the soil. This is because of the high CEC of Vertisols. Studies conducted in Barbados (Medford, 1963) indicated that if the Vertisol is alkaline and moist, and if the fertilizer is surface applied, up to 80 % of it can be lost within one week of application due to the volatilization of ammonia.

2.14 Addition of Phosphorus to the Soil

Plants take up phosphorus as $H_2PO^-_4$ and HPO^{2-}_4. The amount of either $H_2PO^-_4$ or HPO^{2-}_4 depends on the pH of the soil. At pH of 7.2, there are approximately equal amounts of both (Tisdale and Nelson, 1985). In most agricultural soils $H_2PO^-_4$ predominates.

For normal plant growth, the phosphorus concentration in the soil solution is very important. The nature of the crop and the level of production required will determine the required level of P concentration in the soil. According to Fox (1982), yield of corn can be obtained when soil P concentration is as low as 0.01 mg/kg if the yield potential is low. According to Beckwith (1964), even though different crops differ in their requirement for P, a value of 0.2 mg/kg is suggested as the level at which most plants attain maximum growth. The effectiveness of P application depends on the absorption characteristics of the root system and the adsorption properties of the soil (Barber, 1977).

The effect of soil moisture on phosphate availability in Vertisols is very important. According to Le Mare (1987), plant response to phosphate application tend to be smaller and less consistent in irrigated and flooded soils than in soils under rainfed conditions. In flooded Vertisols, iron exist as Fe^{2+} but when soils dry the iron is oxidized and forms poorly crystalline ferric hydrous oxides. These may react with phosphate to diminish phosphate availability. The

phosphate becomes available when the iron is reduced after the soil is wetted again. Turner and Gilliam (1976a, 1976b) recognised that rice in low-land flooded Vertisols responded less consistently to phosphate than crops in similar upland soils. They explained that the better availability of phosphate in flooded soils was related to improved diffusivity, caused by decreased tortuosity.

Many fertilizer trials conducted on Vertisols at Kpong (Oteng, 1974) indicated that though available P is low, phosphatic fertilizer response to trials has not been significant, a situation which could be attributed to the high sorption maximum of these Vertisols. However, available field data from trials on the Vertisols at Kpong also indicated that phosphate is probably weakly held in the Vertisols, and that it maintains concentration which is adequate to prevent severe deficiencies in many crops (Oteng, 1974). According to Cobbina (1975), in order to obtain maximum dry-matter yield on Vertisols, it would be necessary to apply enough fertilizer to supply between 120-180 % of the P sorption maximum.

According to Munk and Rex (1990), generally, continuous P application at a level exceeding P extraction resulted in greater increase in P soil test values than the comparative decrease following P extraction at the same rate. Investigation done by Rao and Subba-Rao (1991), showed that pearl millet and sorghum responded significantly to applied P in six representative Vertisols of India with low available P (2.8 - 7.0 mg/kg). They stated that the requirement of high doses of P for optimum yields was attributable to strong P fixation capacities ranging from 43 to 75 %. According to them, P uptake by both crops was significantly influenced by pH, P fixation capacities of the soil as well as the applied and soil P. Rao *et al.* (1990) reported that increasing P_2O_5 rates up to 60 kg/ha on Vertisols with low P increased the P and K contents of Phaseolus (*Vigna mungo*) but increase in N content was not significant. Jamuna *et al.* (1991), working on requirement of coriander in Vertisols with low available P, reported a decrease in N and an increase in P and K contents of the plant at both flowering and at harvest as the level of P in the soil increased. Ahenkorah and Akrofi (1969) noted that crop responses to P application varied from season to season and from site to site.

This, they argued is because the phosphate that is removed by chemical extraction is affected not only by the amount and nature of the phosphate present but also by the capacity of the soil to sorb phosphate from solution. Variation in P response among crops at the same site is mainly due to the complexity of soil P.

According to Finck and Venkateswarlu (1982), important soil factors affecting the availability of applied P include soil moisture, native available P, nature of the clay and the amount of clay. The quantity of P added and P-sorption capacities of the soil affects the plant P concentration, the dry matter yield and the P-uptake (Kuo, 1990). Venkateswarlu (1979) reported fairly small response to P application under receding moisture conditions of post-rainy season crops at several locations in India. Singh and Venkateswarlu (1985) in their studies reported that response of dry-land crops to P application did not become distinct as long as yield continued to be low.

According to Ahmad (1989), there is often a discrepancy between predictions made from chemical soil tests and crop response to P fertilizer in many Vertisols. Reasons for this observation include poor root development of the crop, poor placement of fertilizer, fixation of P in more unavailable forms in soils with high pH, and for graminaceous crops, the intimate contact of soil and roots in which the plant is able to obtain adequate P from a relatively small volume of exploited soil.

Katyal and Venkatramaya (1983) reported that in a phosphate deficient Vertisols in Andhra Pradesh, India, the concentration of P was influenced only slightly by flooding, but it was 2.5 times greater in the wet than in the dry seasons. This effect was attributed to the temperature which was 10 °C higher in the first two months of the wet season than in the corresponding dry season.

Small response to phosphate application was reported by ICRISAT (1984), although the estimated available phosphate was small. According to Le Mare (1987), the small response to phosphate in apparently deficient soils may occur because only a small amount is released throughout a large volume of soil, so that the total of available-P to a deep rooting crop is adequate for it to achieve the yield potential set by the limitations of other factors.

Malewar *et al.* (1984) found a close relationship between grain yield of sorghum grown on a Typic Chromustert and availability of N measured either by $KMnO_4$ extraction or NO_3-N. Yields of cotton grown on the Vertisols of the Gezira in Sudan were positively correlated with NO_3-N content of the soil profile (Crowther, 1954). Rego et al. (1982) reported that 1 m of soil profile accumulated 65-72 kg of NO_3-N/ha with cropping. This finding suggested that there occurred accumulation of NO_3-N in the profile during the rainy season. Despite a build up of N during the post rainy fallowing, response to N application was significant.

Under irrigation, when higher yields were attempted with increasing application of N higher responses to fertilizer P were also obtained (Sharma and Kant, 1977; Mathan et al., 1978). In Sudan Gezira, application of P to irrigated wheat increased significantly the uptake of soil and fertilizer - N and resulted in higher grain and straw yields (Ayoub, 1986). In the Mediterranean environment of Syria, N application in the absence of P fertilizer on Vertisols tended to decrease barley yields at the drier sites (Harmsen *et al.*, 1983).

2.15 Residual effect of applied phosphorus

Crop uptake of P is usually less than that of N and K. According to Barrow (1980), the losses of P from the soil system is, however, small. This means that when fertilizer P is applied, any amount in excess of crop uptake will remain in the soil and will have some degree of availability to the succeeding crop. Kamprath (1967) showed that a large initial application of P (678 kg/ha) to high P fixing soil had a marked residual effect on maize yields nine years after application.

The duration and magnitude of the residual effect depend largely on the rate of the initial application, crop removal and the buffering capacity of the soil for phosphorus. The absolute residual value is not easily measured (Black and Scott, 1956). Fitter (1974), measured the changes of P through time in the P extracted by bicarbonate.

According to Ahmad (1989) fertilizer is commonly surface applied especially as side dressing. Since internal movement of water in wet Vertisols is almost negligible, leaching of the applied P fertilizer will be minimal. Tillage would incorporate this into a greater depth of soil for the benefit of the succeeding crop. Response to phosphate by crops is sometimes related to water supply (Le Mare, 1987). Ferric hydrous oxides may adsorb phosphate when Vertisols are dry, but some are released when they are flooded and iron is reduced. Since the purpose of applying any fertilizer is to increase yield, the ultimate measure of the residual value of any fertilizer is its ability to support crop growth.

2.16 Plant nutrient uptake

The percent nutrient concentration in the crop multiplied by the total dry matter weight gives the total uptake for a given time interval. It is well known that when one factor such as nutrient supply, temperature or moisture level of the soil is varied, the nutrient concentration of the crop also varies. Prevot and Ollangnier (1956) have expressed "a law of the minimum and balanced nutrition" which can be applied to any factor which then limits yields. This law states that "when one factor which influences growth becomes optimum, one or several others become limiting".

Steenbjerg and Jakobsen (1962) analyzed the complex relationship between available amounts of nutrient element in the soil or substrate, its concentration in the plant tissue and the resulting growth or yield. They concluded as follows:

1 In cases of severe deficiency, the concentration decreases with the first application of the nutrient due to stimulated growth and subsequent dilution of the particular mineral element by increased formation of organic matter.

2. Less severe deficiency may correspond with a situation where the nutrient content of the

plant remains fairly constant despite increasing available amounts. This occurs when greater uptake is compensated by growth and formation of organic matter.

3. The next stage consists of a regular response relationship until the optimum leaf concentration is reached, corresponding with maximum growth and yield.

4 Finally, no further growth increase is obtained of a continuing accumulation of the nutrient element in the plant, which is termed as luxury consumption and may be followed by an adverse effect of toxicity.

According to Dexter (1979), just as the soil structure is found to influence the ability of roots to absorb nutrients, it is also found that the nutrition of the roots influences their behaviour in structured soil. The ability of the plant to absorb a nutrient element in the soil environment is reflected in the nutrient element concentration in the plant or its specific part at any one time. Plant analysis is a measure of the soil-plant nutrient element in soil environment. Soil and plant analysis technique when used together can effectively evaluate the soil plant nutrient environment by confirming the need for a particular element and specifying corrective treatments.

2.17 Nutrient balance

Wallingford (1991) has defined nutrient budget as a "balance sheet showing nutrient removal and additions". Nutrients are exported when plant materials or animal products are sold off the farm. Nutrient can be imported in animal feeds, off-farm waste product and commercial fertilizer added to the soil or by legume fixation of nitrogen.

According to Weeks and Miller (1948), if after several years, P application is discontinued crop yields and the phosphorus content of the crop will begin to decline. This decline will be slow at first, but will increase steadily until it approaches those of the untreated soil. Also, the rate of decline is dependent on the soil, the amount of the fertilizer used, the cropping system and the general fertilizer and soil management practices of the farmer.

Jadhav (1989) reported that after three years of cropping on a Vertisol, total N and available P showed a positive balance under a groundnut - wheat sequence, whereas a negative balance was observed under sorghum-wheat cropping system. Available potassium declined in both sequences. Total N, available P and K balance was negative but the decrease was less with later sowing dates and with increased fertilizer application to wheat. Patel *et al.* (1989), reported a similar observation. They further reported that, treatments with added P resulted in an increase of soil P but there was a negative balance in treatment with no P. The calculated losses of N and P increased with increase in the levels of their application.

2.18 Agronomic efficiency

According to Katyal et al. (1987), agronomic efficiency is expressed as follows:

i) the increase in yield per amount of nutrient applied (expressed as kilogram of yield due to fertilizer per kilogram of fertilizer nutrient), and

ii) the proportion of nutrient taken up by the crop, expressed as percentage of nutrient taken up of the amount applied.

Kanwar and Rego (1983), working on Vertisols of India observed that agronomic efficiency depends on the native fertility of the soils. The higher the native fertility, the lower the response will be.

The P dynamics of soils, variations in soil test values and variations in the amount and nutrient contents of plant residues or manure render estimates for fertilizer requirements unreliable. The optimum fertilizer application according to individual trials, however, is a reliable quantity.

CHAPTER THREE

3 MATERIALS AND METHODS

3.1 The experimental site

The experiment was conducted on the Vertisols of the coastal Savanna Zone of Ghana. The three experimental sites chosen for the research were :

i) University of Ghana Agricultural Research Station (Kpong) for the On-Station trial.

ii) Buedo Farms - for On-Farm trial as site 1 (On-Farm 1)

iii) New Frontier Farms - for On-Farm as site 2 (On-Farm 2)

3.1.1 Climate

The major rainy season starts from March and lasts until July, then a short dry spell that runs till the end of August. The minor rainy season starts from early September and ends in mid-November. There are about 71 to 80 rainy days in a year throughout the experimental areas (Ahenkorah *et al*., 1994). Table 3.1 below shows mean monthly maximum and minimum temperature and monthly total rainfall recorded over the experimental period from September, 1994 to January, 1995.

3.1.2 Vegetation and land use

The vegetation of the area is generally savanna grassland with scattered coppice shoots and trees. The dominant species were *Vetivera fulvibarbis*, *Schzachyrium semiberbe, Euclasta condylotrica, Andropogon canaliculatus*

Table 3.1. Total monthly rainfall and monthly mean temperature distribution of the area during the experimental period.

Month	Total rainfall (mm)	Monthly mean Temperature (°C)	
		Minimum	Maximum
September	207.40	24.8	29.0
October	154.90	25.3	30.5
November	118.40	25.0	30.7
December	0.00	23.7	30.2
January	0.00	24.5	30.0

Andropogon gayanus, Sporobolus pyramidalis, Heteropogon contortus, Imperata *cylindrica*. The dominant tree species are *Combretum ghasalense*, *Anona senegalensis* and *Ceiba pentandra*. About 14 different crops are cultivated within the experimental area. These include maize (*Zea mays*), rice (*Oryza sativa*), cassava (*Manihot utilissima*), pepper (*Capsicum annuum*), okra (*Hibiscus esculentus*) and tomatoes (*Lycopersicum esculentum*) (Dua Yentumi *et al*.,1992a).

3.1.3 Site description

3.1.3.1 On-station trial (A. R. S. Kpong)

The soil at the on-station trial site is Akuse series and is classified as Calcic Vertisol (FAO, 1990). The site has less than 2 % slope. The parent material is colluvial material derived from weathered garnetiferous hornblende gneiss, deposited on similar material. The drainage is class 3, i.e. moderately well drained (Ahenkorah *et al.*, 1993). The site was an old sugarcane field. It was cropped with maize and cowpea in the 1993 farming season. The dominant weed species are the Andropogon spp. *Sporobolus pyramidalis* and *Imperata cylindrica*.

3.1.3.2 On-farm site 1 (Buedo Farms)

The soil at the site is referred to as Tachem series and is classified as Eutric Vertisol (FAO,1990). The farm is located about 1.2 km from the Agricultural Research Station (ARS) on the Accra-Kpong road. The relief is almost flat. The vegetation has *Andropogon canaliculatus, Andropogon gayanus* and *Imperata cylindrica* with fringing thicket nearby. The parent material is alluvial clay derived mainly from basic gneiss and to a less extent from Togo quartzite schist of the nearby Akwapim ridge. The drainage is class 2 i.e. imperfectly drained (Ahenkorah *et al.*, 1993). The land was previously cropped with maize. The dominant weeds are Andropogon species and Imperata cylindrica.

3.1.3.3 On-farm site 2 (New Frontier Farms)

The soil at the site is Bumbi series and is classified as Calcic Vertisol (FAO, 1990). The farm is located about 2.5 km south of ARS along Accra - Kpong road. The site has undulating landscape of low relief with gentle slope of < 2 %. The parent material is an old river terrace alluvial clay derived mainly from basic gneiss and to a lesser extent from Togo quartzite schists of the nearby Akwapim Ridge. The drainage is class 3 i.e. moderately well drained. The site was previously used for sugarcane cultivation and has thicket, forb regrowth and grasses such as *Andropogon species* and *Imperata cylindrica*.

3.2 Experimental Layout

3.2.1 On-station trials

Each plot measured 9.6 m wide and 30 m long. There were four replications. The entire experimental area was 4608 m^2 (0.46 ha). The Ministry of Food and Agriculture recommended rate of fertilizer application for the area is 250 kg/ha, 15-15-15 compound fertilizer and 125 kg/ha of urea applied as top dressing. The fertilizer treatment used were 0 50 and 100 % of the recommended rate. Each of the four Landform (F, R, EB, and CB) was split into three plots measuring (9.6 m x 10 m) to accommodate the three levels of the fertilizer treatment (Fig. 3.1).

3.2.2 On-farm trials

The on-farm trials had two landforms each; Cambered and Flat bed. Each plot had the same dimensions as the on-station trials. There were three replicates. The entire experimental area for each on-farm site was 1728 m^2 (0.17 ha). Only 50 % of recommended rate was applied. This was to enable the two Landforms to be compared at a single fertilizer level and also to meet most farmers request since they are unable to afford the recommended rate.

3.3 Land preparation

The fields were slashed with a tractor-mounted slasher, ploughed and harrowed after the early rains. Ploughing and harrowing were repeated. The Landforms were prepared using the various implements as follows :

Landform	Method of Preparation
a) Flat Bed	The land was ploughed, harrowed and levelled (Fig. 3.2a)
b) Ridge Bed	The land ploughed, harrowed and a Ridger mounted on a tractor prepare the ridges (Fig. 3.2b)
c) Ethiopian Bed	The land ploughed, harrowed and a Tractor tool carrier used in shaping the Ethiopain bed (Fig. 3.2c)
d) Cambered bed	The land ploughed and harrowed and a Polydisc (one way Disc harrow) used for making the cambered bed (Fig. 3.2d).

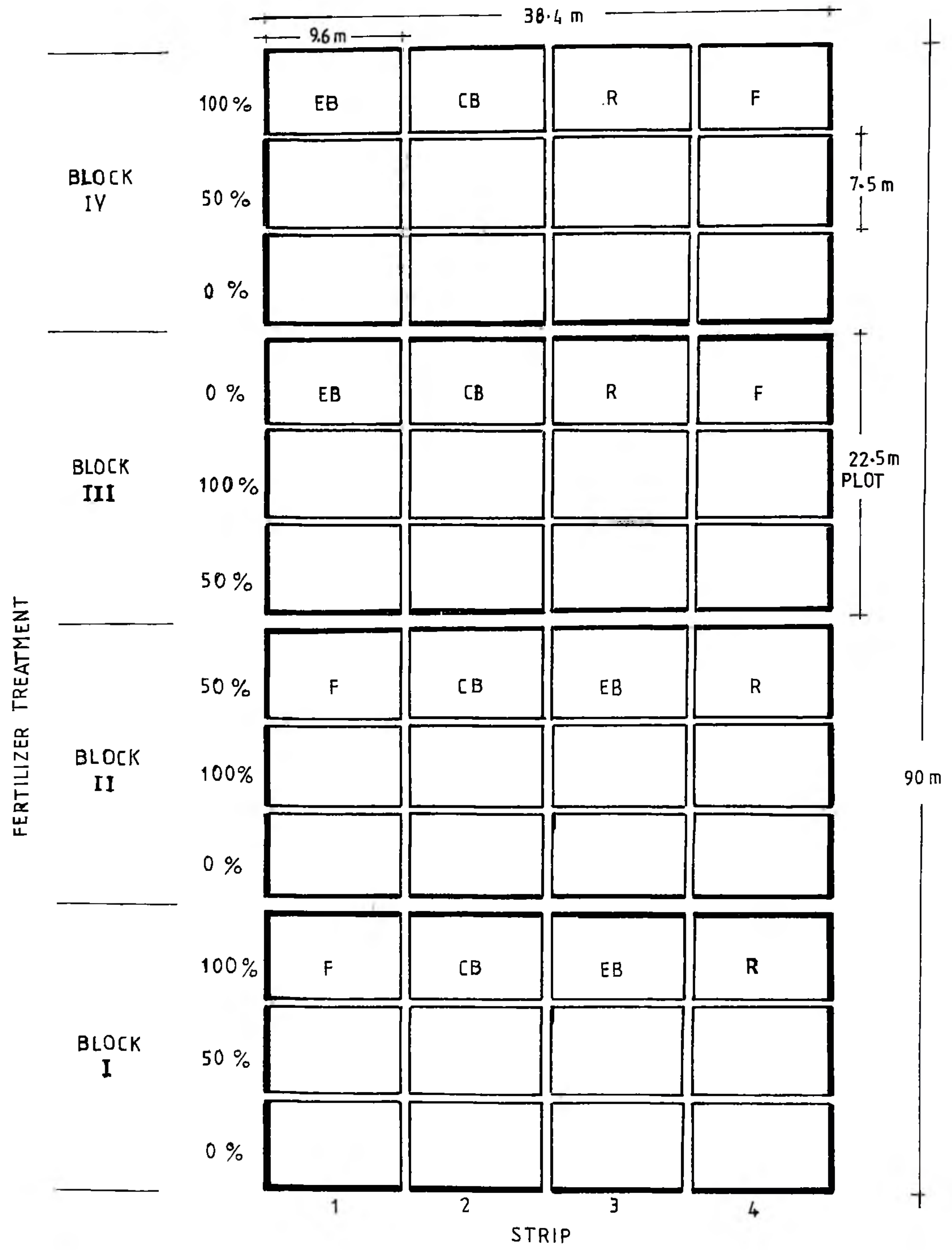

Fig. 3.1 Field layout - The four Landforms with three fertilizer levels at A. R. S.-Kpong.

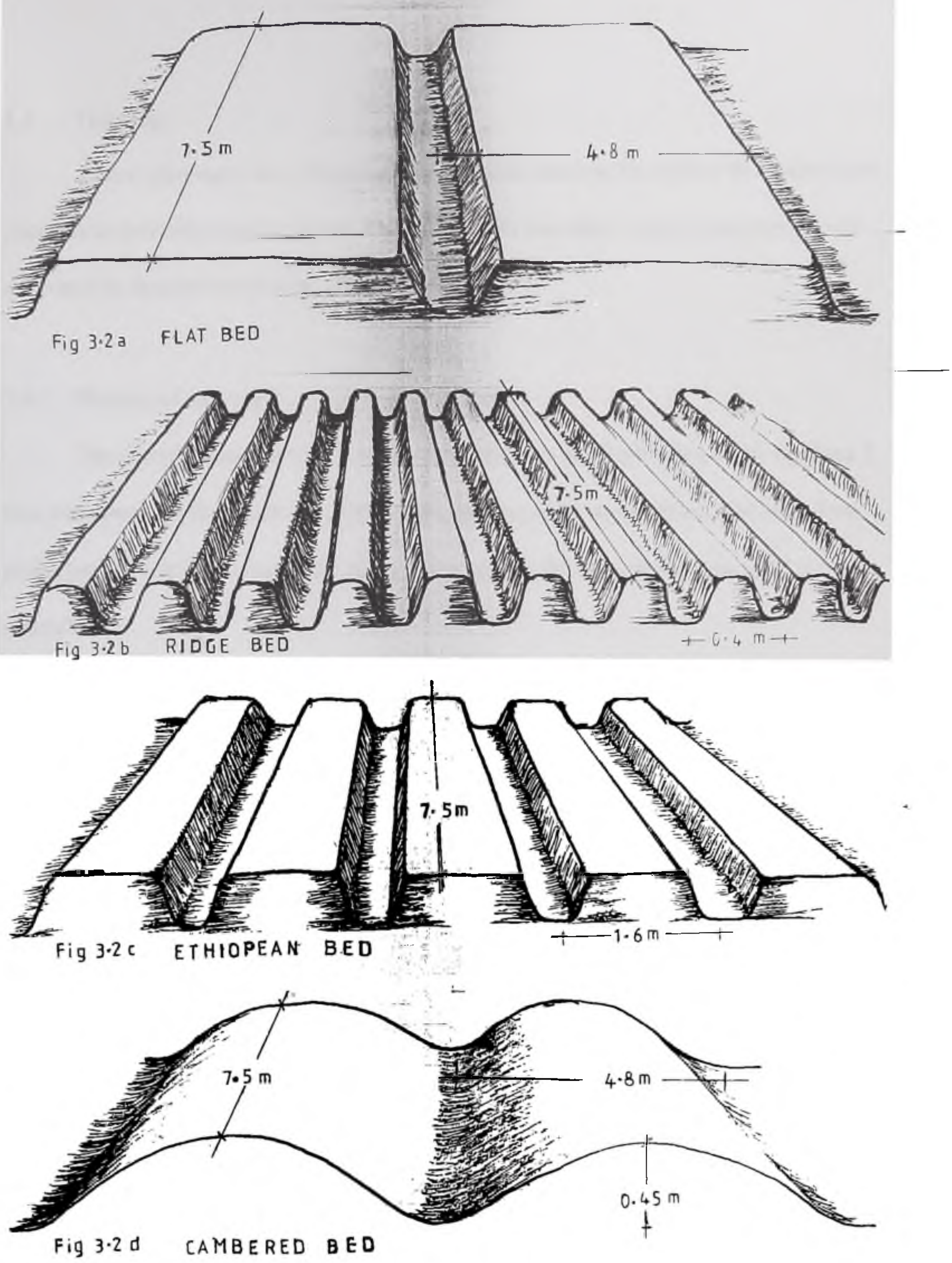

Fig.3.2. Diagrammatic representation of the four Landforms.

3.4 Test crop

Maize (*Zea mays* Var. Obaatanpa) was used as test crop because of its sensitivity to phosphorus deficiency (Ardeeva and Andreeva, 1974) and also it is the most popular crop cultivated by farmers in the area.

3.4.1 Planting of test crop

The on-station and on-farm 1 trials were sowed on 3rd September, 1994. On-farm 2 trial was sowed on 6th September, 1994. Plant spacing of 80 cm by 40 cm was used. Two plants per hill was maintained after germination making the plant population of 62,500 plants/ha.

3.4.2 Fertilizer application

The 15-15-15 compound fertilizer was applied by band placement two weeks after emergence of the crop and top dressed with urea one month later. With the on-station trials, the compound fertilizer was applied on the 24th September, 1994 and was top dressed with Urea on the 28th October, 1994. The compound fertilizer was applied by band placement on 23rd and 28th September, 1994 to farms 1 and 2 respectively.

3.4.3 Weed control

The predominant weeds in all the experimental sites were *Andropogon species* and *Imperata cylindrica*. A knapsack sprayer was used to spray Bellater (Bladex + atrazine) herbicide to control the weeds. This was followed by light hoeing and slashing with cutlass between the 9th and 10th week when weeds had sprung up.

3.5 Soil sampling

A steel augur with a cylindrical tube of 5 cm in diameter was used to sample the soils. Samples were taken to a depth of 15 cm. Five augur samples were taken randomly from each plot, bulked, kept in plastic bags and sent to the laboratory. The soil samples were taken before maize tasselled, at tasselling and after harvesting. The sampling was done on 21st October, 1994, 1st November, 1994 and 10th January, 1995. These samples are referred to as 1st, 2nd, and 3rd samples, respectively. Initial composite soil samples were taken before start of the experiment.

3.6 Plant sampling

Maize ear leaf samples were collected on 22nd November, 1994 at tasselling. The entire ear leaf of five plants per plot was systematically sampled across a diagonal and sent to the laboratory. At maturity (16 weeks after sowing), a sub-sample of five plants per plot were selected. Grains, cob, stubble and roots of these five plants were harvested separately; (stubble here referred to the rest of the maize plant apart from root, cob and grain at maturity). The roots were harvested by loosening the soil around each plant and wetted thoroughly with water.

3.7 Laboratory analysis of soil samples

The soil samples were air-dried, crushed and passed through a 2 mm sieve and stored for physico-chemical analyses. Sample from each treatment was analysed separately.

3.7.1 Soil pH

The pH of each soil sample was measured electrometrically, on a Pracitronic M.V 88 pH glass electrometer both in water at a ratio of 1:1 soil:water and in 1:2.5 soil : 0.01 M $CaCl_2$ solution. The soil-liquid suspension was stirred for 30 minutes and allowed to settle. The electrode was inserted into the suspension to measure the pH.

3.7.2 Particle size analysis

Particle size analysis was carried out by the method of Bouyoucos (1962). To 40 g sample of 2 mm air dried soil was added 100 ml 5 % calgon solution. It was shaken on a rotary shaker for 2 hours. The suspension was transferred to a graduated sedimentation cylinder. Water was added to make it to the litre mark. A plunger was lowered into the cylinder. The reading on the hydrometer was taken after 40 seconds and also after 5 hours. The sand fraction was obtained after decanting the top silt and clay from the sedimentation cylinder using a 0.2 mm sieve. The 0.2mm fraction (sand) was then dried and weighed.

3.7.3 Organic matter determination

Organic carbon content of the soil sample was determined by the method of Walkley and Black (1934). A 0.5 g sample of 0.5 mm sieved soil was weighed into a 250 ml Erlenmeyer flask. It was digested with 10 ml 0.1667 M K_2CrO_4 (1 N) and 20 ml of concentrated H_2SO_4A 50 ml of distilled water was added and titrated with 1.0 M acidified $FeSO_4$. The organic carbon was converted to organic matter by multiplying it with 1.724.

3.7.4 Total nitrogen and total phosphorus determination

A 0.5 g sample of 2 mm sieved soil was digested with 4.4 ml digestion mixture (0.42 g selenium powder, 14 g lithium sulphate and 350 ml 30 % hydrogen peroxide) at 360 ^oC for two hours. Concentrated sulphuric acid (420 ml) was slowly added to the mixture while cooling in an ice bath. After two hours of digestion, the solution was allowed to cool and made up to 100 ml with distilled water (Anderson and Ingram, 1978.)

The ammonia in 25 ml aliquot of the above digested sample was distilled in an alkaline medium with boric acid. The ammonia was then titrated with 0.01 M HCl and nitrogen content calculated (Anderson and Ingram, 1978).

Total phosphorus concentration in 5 ml aliquot of the digested sample was determined colorimetrically by the molybdenum blue colour method of Murphy and Riley (1962). The phosphorus concentration was measured as described below in section 3.7.10.

3.7.5 Exchangeable cations

A 10 g sample of the 2 mm sieved soil was shaken on a mechanical shaker for 1 hour with 100 ml 1 M NH_4OAc solution at pH 7.0. An aliquot of the extract was used to determine the concentration of K and Na by flame photometer while Ca and Mg were determined by atomic absorption spectrophotometer.

3.7.6 Cation exchange capacity

A 10 g sample of 2 mm sieved soil was successively leached with 100 ml 1 M ammonium acetate, 100 ml ethanol and 100 ml 1 N acidified KCl. A 25 ml of 40 % NaOH solution was added to 50 ml aliquot of the KCl leachate. The mixture was distilled into 0.1 M HCl using methyl red as indicator. The distillate was titrated with 0.1 M NaOH solution. The CEC was then calculated using the titre values.

3.7.7 Soil organic phosphorus determination

A 10 g sample of 2 mm sieved soil was placed in a cool muffle furnace. The temperature of the furnace was slowly raised to 550 ^{o}C over a period of 2 hours. The crucible was allowed to cool and content transferred to a 100 ml polypropylene centrifuge bottle. In a separate 100 ml polypropylene centrifuge bottle was placed 10 g unignited soil. To each bottle was added 50 ml 1 N H_2SO_4 and centrifuged for 15 minutes. An aliquot of the clear solution was pipetted and phosphorus content measured as described in section

3.7.10. Soil organic phosphorus was estimated by the difference between the extractable inorganic phosphate concentration in ignited and unignited soil (Legg and Black, 1955).

3.7.8 Available phosphorus

A 10 g sample of 2 mm sieved soil was extracted with 100 ml of 0.5 M NaHC03 solution (Olsen et al., 1954). An aliquot was taken and phosphorus concentration determined as described in section 3.7 10.

3.7.9 Soil inorganic phosphorus fractions

Inorganic phosphorus fractions: Calcium phosphate (Ca-P), Aluminium phosphate (Al-P), Iron phosphate (Fe-P) and Occluded phosphate (Occl-P) were fractionated (Chang and Jackson, 1957, as modified by Peterson and Corey, 1966).

Ten grams of 2 mm soil were sequentially extracted with :

i.) fifty ml of (0.1 M NaCl + 1.0 M NaOH) solution to remove non- occluded Al- and Fe-bound phosphate

ii) two 40 ml portions 1 M NaCl and 45 ml 0.3 M citrate-bicarbonate solution to remove phosphate sorbed by the carbonates during the first extraction;

iii) a 45 ml of 0.3 M citrate-dithionite-bicarbonate to remove P-occluded within Fe oxides and hydrous oxides,

iv) a 50 ml 1 N HCl to remove Ca-P, and finally

v) a 50 ml 0.5 M NH4F to remove Al-P.

3.7.10 Determination of phosphorus concentration in extracts

The phosphorus concentration in all the extracts was determined colorimetrically by the molybdenum blue colour method of Murphy and Riley (1962). All the measurements were done at a wavelength of 712 nm on a PU 8620 spectrophotometer.

3.8 Plant analysis

Leaf, stubble and cob were chopped separately and the roots washed thoroughly of soil particles with water and then chopped. All the plant samples including the grains were oven dried at 70 °C for 48 hours. The dry matter weight of each sample was taken and milled to pass through 0.5 mm sieve. The milled samples were stored for laboratory analysis.

3.8.1 Wet digestion of plant samples

A 0.2 g of ground plant material (leaf, grain, cob, stubble and root) was digested with 5 ml concentrated sulphuric acid on a sandbath for 5 minutes. Using 1 m1 pipette, 30 % hydrogen peroxide was added dropwise until the digested material became colourless. Distilled water was added and heated on the sandbath for the H_2O_2 to evaporate. The solution was allowed to cool, made up to 100 ml with distilled water, and stored for the determination of N P K Na Ca and Mg.

3.8.2 Determination of total nitrogen in plant samples

Total nitrogen in the plant sample was determined by taking 1 ml aliquot of the digested sample. The ammonia in it was distilled in alkaline medium into 20 ml Boric acid indicator solution. The ammonia was then titrated with 0.01 M HCl. (Anderson and Ingram, 1978.).

3.8.3 Determination of K, Na, Ca, Mg contents in plant samples

One ml aliquot was taken from the digested sample. Potassium and Na concentrations were determined by flame photometry; while the Ca and Mg concentration by atomic absorption spectrophotometry (AAS3 Carlzeiss Jena).

3.8.4 Phosphorus concentration and uptake in plant samples

One ml aliquot of digested material was taken for the determination of P by blue molybdenum colour development (Murphy and Riley, 1962). Phosphorus concentration measured at a wavelength of 712 nm on a PU 8620 Spectrophotometer.

The phosphorus uptake was obtained by multiplying the respective dry matter weight by their corresponding phosphorus concentration at a given time interval.

3.9 The relative agronomic efficiency (RAE) of the landforms

The RAE was evaluated using the expression:

$$RAE = \frac{(Yii - fj)}{fj} \times 100$$

where :

Y = dry weight of plant

i = Landform

j = rate of fertilizer applied

f = Flat bed

The Flat bed was used as standard since it is the most common landform used by farmers in the experimental area. The RAE on the Flat bed was assigned 100 %. The RAE of the remaining landforms were expressed relative to that of the Flat bed.

3.10 Statistical Analysis

The experimental design at the on-station site was four Landforms each with three fertilizer levels. The 4 x 3 split-plot design was replicated four times to give 48 experimental plots. Landform was considered as factor A (main plot) and rate of fertilizer application as factor B (sub-plot) (Appendix 1 and 2). Both on-farm 1 and 2 had two Landforms each with one rate of fertilizer application with three replications giving 6 experimental plots in each of the on-farm trial.

The on-station site has all the four landforms: Flat, Ridge, Ethiopian and Cambered bed. Three rates of fertilizer application were 0, 50 and 100 % of recommended rate of fertilizer application were used. The on-farm has Flat and Cambered bed with 50 %

recommended fertilizer application. The recommended rate of fertilizer was 250 kg/ha of 15-15-15 compound fertilizer and 125 kg/ha of urea.

Correlation coefficients between soil variables and plant response were calculated. To be able to identify principal variables that accounted for the variability in dry weight of maize (leaf, root, stubble, cob and grain), the Best Subset Regression technique (Breg) in "Minitab" was used (Mckenzie et al.,1995). If n variables are selected as possible predictors of dry maize weight, the technique selects all one-predictor models and selects as possible the model giving the largest R^2 value. It then looks at two-, three-, up to the n-predictor models in turn and selects models with largest R^2 value. The maximum R^2 value and the smallest mallow's "CP" value (with a value close to the number of variables in the model) statistic were used as the criteria for the selection of the Best Subset (Hocking, 1976) which can then be used to determine the precise regression equation of either dry matter yield or uptake of phosphorus.

Mallow's Cp statistic is defined as:-

$$Cp = \frac{SSEP}{MSEn} \times (n - 2p)$$

Where SSEP = error sum of squares for the best model with P variables (including intercept) and MSEn is the mean square for the model with all n predictors. Appendices 2 and 3 show examples of Best Subset Regression analysis.

CHAPTER FOUR

4 RESULTS

4.1 Initial general characteristics of the soils

The pH in water of the soil sampled from the experimental sites before the start of the experiment ranged 6.60 - 7.03 with a mean of 6.81. The pH in 0.01 M $CaCl_2$ ranged from 5.98 to 6.27 with the mean of 6.12. Particle size analysis indicated 28.3 - 32.5 % sand; 16.5 - 20.9 % silt; and 49.5 - 51.8 % clay. The soil organic matter content at the 2 on-farms ranged from 2.3 - 2.4 % was generally higher than organic matter at the on-station which ranged 1.9 - 2.3 %. Soil nitrogen at the on-farm sites ranged from 0.165 to 0.193 %, while the of on-station ranged 0.127 - 0.135 %. The trend of exchangeable cation at all the experimental sites was Ca >> Mg > Na > K [21.6 >> 7.5 > 1.1 > 0.4 c mol (+)/kg soil] respectively. Generally the soils at the on-station had higher exchangeable cations than the soils at the on-farms. Cation exchange capacity at all the experimental sites ranged 27.28 - 29.93 cmol/kg soil.

Total P at the on-farms ranged from 380.70 to 392.85 µ/g and was higher than the total P at the on-station with values ranging from 351.29 to 373.13 µ/g. The organic P content was also higher at the on-farm than at the on-station. The inorganic P fractions at all the experimental sites followed the trend: Ca-P >> Al-P > Avail.-P > Occl.-P > Fe-P.

4.2 Total phosphorus in the soil

Total P (TP) in the soil at the on-station site ranged between 338 and 442 μ/g. Neither landforms nor phosphorus treatment significantly influenced the total P in all the experimental sites. The rate of fertilizer applied, however, had significant influence on total soil P before maize tasselled (Table 4.1) . The 100 % fertilizer level indicated a slightly higher total P on the Ridged bed than the rest of the Landforms, though the differences were not significant.

Table 4.1. Soil total P in the four Landforms at different levels of fertilizer application before the maize tasselled.

Landform	Rate of fertilizer applied (%)			Landform mean	CV (%)
	0	50	100		
On-station	------------------μg P g^{-1} -----------------				
Flat bed	379.00	400.80	384.70	388.17	
Ridged bed	402.40	357.50	442.20	400.70	6.93
Ethiopian bed	413.00	338.60	358.60	370.07	
Cambered bed	388.10	366.60	364.40	367.09	
Fertilizer mean	395.62 a	365.85 b	382.97 ab		
On-farm 1					
Flat bed		426.53			9.62
Cambered bed		438.93			
On-farm 2					
Flat bed		475.51			8.80
Cambered bed		475.07			

Rate of fertilizer applied mean LSD ----25.59**

Treatment means followed by the same letter are not significantly different according to the Duncan's Multiple Range Test.

* * Significant at $P < 0.01$

Total P in the Landforms did not follow any definite pattern. At the two on-farm sites there was no significant difference between total P in the Flat bed compared to the Cambered bed.

After the maize had tasselled, total P concentration of the soils ranged between 371 and 420 µg/g. Neither the Landform nor the fertilizer application significantly influenced total P levels in the soil (Table 4.2). The zero rate of fertilizer application seems to have slightly greater total soil P values.

Table 4.2. Soil total P in the four landforms at different levels of fertilizer application after maize had tasselled.

Landform	Rate of fertilizer applied (%)			Landform mean	CV (%)
	0	50	100		
On-station	-------------µg P g^{-1}	-------------------			
Flat bed	414.60	391.00	405.00	405.00	
Ridged bed	405.82	419.92	408.81	408.81	7.68
Ethiopian bed	418.33	404.80	408.74	408.70	
Cambered bed	386.60	400.20	393.53	393.53	
Fertilizer mean	406.34	403.98	401.75		
On-farm 1					
Flat bed		396.13			2.29
Cambered bed		402.27			
On-farm 2					
Flat bed		387.87			2.99
Cambered bed		371.07			

The total P levels in the soil after the maize had been harvested ranged between 371 and 496 µg/g. As in the two previous samples, neither the Landforms nor the fertilizer rate significantly influenced total P levels in the soil. The range in total P level at this stage was higher than before and after maize had tasselled. During the growing period of maize, no significant correlation was found between the total soil P and either the dry weight or the P uptake of the crop.

Table 4.3. Soil total P in the four Landforms at different levels of fertilizer application at the maize harvest.

Landform	Rate of fertilizer applied (%)			Landform mean	CV (%)
	0	50	100		
On-station	------------µg P g^{-1}	-------------------			
Flat bed	390.29	398.80	399.26	399.26	13.92
Ridged bed	390.97	391.75	399.27	399.27	
Ethiopian bed	419.65	407.00	417.79	417.79	
Cambered bed	371.30	396.92	395.64	395.64	
Fertilizer mean	393.05	398.62	398.62		
On-farm 1					
Flat bed		496.53			6.36
Cambered bed		491.20			
On-farm 2					
Flat bed		484.60			4.44
Cambered bed		448.00			

4.3 Organic phosphorus in soil

Soil organic phosphorus before the maize tasselled ranged between 89 and 110 µg/g for the on-station and between 123 and 130 µg/g for the on-farm trials. The differences in organic P content between the Landforms were significant. Fertilizer application significantly reduced soil organic P levels (Table 4.4). The effect of levels of P applied and Landforms significantly influence the soil organic P content at the on-station site. There was a decreasing trend of soil organic P with 0, 50 and 100 % rate of application. There was no significant difference in soil organic P between the two Landforms at both on-farm sites. There was a significant negative correlation between the soil organic P and the dry matter yield. The soil organic P before the maize tasselled was selected among the best variables predicting maize yield.

Table 4.4. Soil organic P in the four Landforms at different levels of fertilizer application before maize tasselled.

Landform	Rate of fertilizer applied (%)			Landform mean	CV (%)
	0	50	100		
On-station	------------$\mu g\ P\ g^{-1}$	---------------------			
Flat bed	99.22 bc	100.01a	97.50 ab	97.50 ab	
Ridged bed	110.30a	96.94 ab	100.30a	100.30 a	4.85
Ethiopian bed	94.85 d	91.67 c	92.44 b	92.44 b	
Cambered bed	108.70a	95.30 bc	95.38 ab	95.38 ab	
Fertilizer mean	103.27a	95.98 b	89.96 b		
On-farm 1					
Flat bed		124.70			4.41
Cambered bed		130.02			
On-farm 2					
Flat bed		123.16			5.57
Cambered bed		117.78			

Within column mean LSD --------9.52**

Rate of P applied mean LSD ----4.62**

Landform mean LSD--------------5.93**

Treatment means followed by the same letter within a column are not significantly different according to the Duncan's Multiple Range Test.

** Significant at $P < 0.01$

After the maize had tasselled, the soil organic P ranged between 89 and 102 µg/g for on-station and 108-126 µg/g for the on-farm. The differences in soil organic P between the Landforms and different rates of fertilizer application were not significant. At the two on-farms there was no significant difference in soil organic P between the two Landforms.

Table 4.5. Soil organic P in the four Landforms at different levels of fertilizer application after maize tasselled.

Landform	Rate of fertilizer applied (%)			Landform mean	CV (%)
	0	50	100		
On-station	-----------$\mu g\ P\ g^{-1}$-----------------				
Flat bed	102.27	99.89	98.90	98.90	12.50
Ridged bed	90.32	98.07	93.33	93.33	
Ethiopian bed	95.08	89.32	90.56	90.56	
Cambered bed	93.26	96.73	92.96	92.96	
Fertilizer mean	95.23	96.00	90.58		
On-farm 1					
Flat bed		126.43			4.62
Cambered bed		126.15			
On-farm 2					
Flat bed		111.70			5.96
Cambered bed		108.58			

The correlation coefficient between organic P and dry matter weight of maize at tasselling was not significant.

Soil organic P ranged between 95 and 105 µg/g for the on-station and between 125 and 159 µg/g for the on-farm after maize has been harvested (Table 4.6). Organic P due to rates of fertilizer applied was not significant, and also there were no significant differences between the Landforms at the on-station and the on-farm 1. At on-farm 2, however, organic

P was significantly higher in the Cambered than in the Flat beds. In general, throughout the maize growing period, the organic P was lower (range 82-109 μg/g) in on-station than on-farm trials (ranged 124-159 μg/g). With respect to the on-farm, the organic P content in on-farm 1 has a narrower range (124-130 μg/g) than on-farm 2 (108-159 μg/g).

Table 4.6. Soil organic P in the four Landforms at different levels of fertilizer application at the maize harvest.

Landform	Rate of fertilizer applied (%)			Landform mean	CV (%)
	0	50	100		
On-station	------------μg P g^{-1}	------------------			
Flat bed	97.60	95.90	97.88	97.88 ab	
Ridged bed	102.57	104.10	105.35	105.35 a	8.05
Ethiopian bed	101.79	94.27	96.86	96.86 ab	
Cambered bed	103.93	100.37	102.49	102.49 ab	
Fertilizer mean	101.47	98.66	101.80		
On-farm 1					
Flat bed		125.48			2.91
Cambered bed		127.47			
On-farm 2					
Flat bed		133.65 b			2.45
Cambered bed		159.07a			

Landform mean LSD---------------7.48*

Treatment means followed by the same letter with a column are not significantly different according to the Duncan's Multiple Range Test.

* Significant at $P < 0.05$

4.4 Soil available phosphorus

Results of the soil analysis before maize tasselled indicated a decreasing trend of available P as Ridged = Ethiopian > Cambered ≥ Flat bed. These differences were significant at $P<0.01$. The content of soil available P was highest at 50 % rate of fertilizer application where the mean was about twice the value for either 0 or 100 % rate of fertilizer application. The range of available P for the for on-station soils was 2.63 - 7.63 μg/g and 5.22 -6.79 μg/g for the on-farm. In both on-farm 1 and 2, differences in the soil available P in the two Landforms were not statistically significant though in all cases the Cambered bed had higher available P than Flat bed (Table 4.7). The available P content was significantly influenced by the interaction between rate of P and Landform. The highest available P occurred on the Ridged bed at 50 % fertilizer application but least at 0 %. There was a positive significant correlation between available P and the dry matter weight of stubble, root, cob, grain.

Soil available P after the maize had tasselled ranged between 3.29 and 4.66 μg/g for on-station and between 4.15 and 4.83 μg/g for the on-farm sites (Table 4.8). The differences between the Landforms were significant at $P < 0.05$ while the difference as a result of fertilizer levels were not significant. At 100 % fertilizer application, the available P content of soil was consistently high in all the Landforms without any significant differences with a mean value of 4.37 μg/g. However, at zero fertilizer rate a decreasing trend of F = CB > E = R was observed, though the differences were not significant.

Table 4.7. Soil available P on the four Landforms at different levels of fertilizer application before the maize tasselled.

Landform	Rate of fertilizer applied (%)			Landform mean	CV (%)
	0	50	100		
On-station	-------------μg P g^{-1} ---------------				
Flat bed	3.48 a	4.60 b	3.66 b	3.66 b	11.38
Ridged bed	2.63 a	7.63 a	4.73 a	4.73 a	
Ethiopian bed	3.54 a	6.85 a	4.67 a	4.67 a	
Cambered bed	2.72 a	6.71 a	4.11 ab	4.11 ab	
Fertilizer mean	3.09 b	6.45a	3.34 b		
On-farm 1					
Flat bed		5.22			9.26
Cambered bed		6.55			
On-farm 2					
Flat bed		5.70			16.84
Cambered bed		6.79			

Within column mean LSD --------0.97**

Rate of fertilizer applied mean LSD ----0.48**

Landform mean LSD--------------0.69**

Treatment means followed by the same letter within a column are not significantly different according to the Duncan's Multiple Range Test.

** Significant at $P < 0.01$

After harvest, the mean available P decreased to about half the value before the tasselling stage on the fertilizer treated plots (compare Tables 4.7 and 4.9). There appears to be no definite trend in the available P with respect to the landforms. In on-farm 1, soil available P in the Cambered bed was significantly higher than that of the Flat bed. In on-farm 2, however, there was no significant difference between the two Landforms.

Table 4.8. Soil available P in the four Landforms at different levels of fertilizer application after maize had tasselled.

Landform	Rate of fertilizer applied (%)			Landform mean	CV (%)
	0	50	100		
On-station	--------- ---μg P g⁻¹ ---------------				
Flat bed	4.66	4.64	4.26	4.52 a	20.34
Ridged bed	3.78	3.69	4.51	3.99 b	
Ethiopian bed	3.29	3.75	4.41	3.82 b	
Cambered bed	4.13	4.24	4.30	4.22 ab	
Fertilizer mean	3.97	4.08	4.37		
On-farm 1					
Flat bed		4.46			5.00
Cambered bed		4.15			
On-farm 2					
Flat bed		4.83			3.51
Cambered bed		4.37			

Landform mean LSD--------------0.48*

Treatment means followed by the same letter within column are not significantly different at according to the Duncan's Multiple Range Test.

* Significant at $P < 0.05$

were not significant. At 50 % fertilizer application, the available P was clearly superior at

In general, notwithstanding the fertilizer level, the drop in available P during the entire maize growing period was 15 % in the F, 35 % in the R, 30 % in the EB and 29 % in the CB over the initial available P levels in the soil. This trend indicates that the drop was twice in the raised beds than the Flat bed. The correlation between available P and dry matter weight was significant and the correlation coefficient at tasselling was higher than before tasselling. Available P was selected among the best subset of predictor variables in dry matter production.

Table 4.9. Soil available P on the four the Landforms at different levels of fertilizer application at maize harvest.

Landform	Rate of fertilizer applied (%)			Landform mean	CV (%)
	0	50	100		
On-station	----------μg P g^{-1} ---------------				
Flat bed	3.22	3.23	2.95	3.13	22.92
Ridged bed	3.03	3.17	2.95	3.05	
Ethiopian bed	3.30	3.40	3.40	3.23	
Cambered bed	2.87	3.01	2.88	2.92	
Fertilizer mean	3.10	3.20	2.94		
On-farm 1					
Flat bed		3.95 b			3.88
Cambered bed		4.69a			
On-farm 2					
Flat bed		3.51			5.81
Cambered bed		3.55			

$P < 0.05$.

4.5 Calcium phosphate

Calcium bound P (Ca - P) in the soil was the most dominant inorganic P. Its content before the maize tasselled ranged from 17.92 to 25.37 μg/g for the on-station and 19.50-28.93 μg/g for the on-farms (Table 4.10). There were significant differences between the Landforms. Calcium- bound P in the Cambered bed was significantly lower than that of the Ethiopian bed while Ca-P in the Flat, Ridged and Ethiopian beds were not significantly different. Addition of fertilizer resulted in significant drop in Ca-P level of the Cambered bed. Differences in Ca-P between the two Landforms in both on-farm 1 and 2 were significant at $P < 0.05$ with the Cambered bed having greater content than the Flat bed.

Table 4.10. Soil calcium P in the four Landforms at different levels of fertilizer application before the maize tasselled.

Landform	Rate of fertilizer applied (%)			Landform mean	CV (%)
	0	50	100		
On-station	---------------µg P g^{-1} ---------------------				
Flat bed	24.35 a	22.42 a	21.10 b	22.62 ab	7.33
Ridged bed	23.20 a	22.80 a	24.60a	23.53 ab	
Ethiopian bed	24.20 a	23.72 a	25.37a	24.43 a	
Cambered bed	25.37 a	17.92 b	19.55 b	20.60 b	
Fertilizer mean	24.02 a	21.72 b	22.66 ab		
On-farm 1					
Flat bed		19.50 b			5.75
Cambered bed		25.60a			
On-farm 2					
Flat bed		23.03 b			15.33
Cambered bed		28.93a			

Within column mean LSD --------3.33 **

Rate of P applied mean LSD ----1.65 **

Landform mean LSD--------------3.12 **

Treatment means followed by the same letter within column are not significantly different according to the Duncan's Multiple Range Test.

** significant at $P < 0.01$

The calcium bound P was negatively correlated with dry weight of maize. The correlation coefficient was significant ($P< 0.05$) with root, cob and grain dry weight.

After the maize had tasselled, soil Ca-P levels ranged between 26.67 and 31.25 µg/g for the on-station trial and 40.89 to 42.22 µg/g for the on-farm (Table 4.11). There were no significant differences in Ca-P in the four Landforms. Generally, the Ca-P after the maize had tasselled was higher than either before tasselling or after the maize harvest (compare

Table 4.11 to 4.10 and 4.12). Also at 50 % fertilizer application the Ca-P was higher in the CB than the other three Landforms. The correlation between Ca-P and dry weight after the maize had tasselled was significant ($P < 0.05$). The least correlation coefficient was obtained between Ca-P and leaf dry weight and highest was with grain dry weight.

Table 4.11. Soil calcium P in four Landforms at different levels of P application after the maize had tasselled.

Landform	Rate of P applied (%)			Landform mean	CV (%)
	0	50	100		
On-station	-----------μg P g^{-1}	---------------------			
Flat bed	28. 00	28.04	27.75	27.93	12.14
Ridge bed	26.67	27.83	26.92	27.14	
Ethiopian bed	27.92	28.96	28.52	28.47	
Cambered bed	26.71	31.25	29.04	29.00	
Fertilizer mean	27.32	29.02	28.03		
On-farm 1					
Flat bed		40.89			1.24
Cambered bed		42.22			
On-farm 2					
Flat bed		41.33			2.51
Cambered bed		41.01			

Soil Ca-P ranged from 23.37 to 26.62 μg/g for on-station and from 30.86 to 36.33 μg/g for the on-farm after maize had been harvested (Table 4.12). There was no significant difference between the fertilizer rate at-station. A significant decreasing trend of EB > R > F > CB was observed among the Landforms.

Table 4.12. Soil calcium P in the four Landforms at different levels of fertilizer application at maize harvest.

Landform	Rate of fertilizer applied (%)			Landform mean	CV (%)
	0	50	100		
On-station	--------------µg P g^{-1} -------------------				
Flat bed	23.96	23.96	23.78	23.90 b	7.39
Ridged bed	25.62	26.62	26.00	26.08 a	
Ethiopian bed	24.12	24.83	23.52	24.17 b	
Cambered bed	23.71	24.17	23.37	23.75 b	
Fertilizer mean	24.35	24.90	24.17		
On-farm 1					
Flat bed		30.86			2.33
Cambered bed		32.61			
On-farm 2					
Flat bed		36.33			4.75
Cambered bed		33.08			

Landform mean LSD--------------1.54*

Treatment means followed by the same letter within column are not significantly different according to the Duncan's Multiple Range Test. * Significant at $P < 0.05$

4.6 Aluminium phosphate

Soil aluminium bound phosphate (Al-P) was the next highest inorganic P after Ca-P. Before the maize tasselled, the Al-P ranged 5.01- 5.77 µg/g for the on-station and 5.55 to 6.05 µg/g for the on-farm (Table 4.13). Differences in soil Al-P in the four Landforms at the on-station were not significant. The difference between the two Landforms at the on-farm 1 was significant at $P < 0.05$ but not at on-farm 2. There was no significant difference in soil Al-P as a result of addition of fertilizer. There was, however, a significant drop in soil Al-P at 100 % fertilizer level in the CB. Soil Al-P at this stage of maize growth did not seem to follow any defined pattern.

Table 4.13. Soil aluminium P in the four Landforms at different levels of fertilizer application before the maize tasselled.

Landform	Rate of fertilizer applied (%)			Landform mean	CV (%)
	0	50	100		
On-station	------------μg P g^{-1} ----------------				
Flat bed	5.51ab	5.17 a	5.50 ab	5.39	6.26
Ridged bed	5.14 b	5.56 a	5.26 ab	5.32	
Ethiopian bed	5.35 ab	5.37 a	5.63 a	5.45	
Cambered bed	5.77 a	5.40 a	5.01 b	5.39	
Fertilizer mean	5.44	5.38	5.35		
On-farm 1					
Flat bed		5.55 b			3.81
Cambered bed		6.05a			
On-farm 2					
Flat bed		5.77			3.35
Cambered bed		5.73			

Within column mean LSD --------0.49*

Treatment means followed by the same letter within column are not significantly different according to the Duncan's Multiple Range Test. * Significant at $P < 0.05$.

Soil Al-P after the maize had tasselled ranged from 5.08 to 5.63 μg/g for the on-station and 5.59 to 6.21 μg/g for the on-farms (Table 4.14). There were significant differences between Al-P content of the four Landforms. Generally the raised beds had significantly lower Al-P content than that of the Flat bed. Different fertilizer levels did not significantly influence Al-P in soil. At 100 % rate of fertilizer application, Al-P after tasselling dropped significantly with F ≥ CB > EB = R. Moreover at 50 % fertilizer rate, the Flat bed had the highest soil Al-P compared with the raised beds though the differences were not significant. At both on-farm sites differences in Al-P in the Landforms were not significant though at the two sites Al-P in the Flat was higher than in the Cambered bed.

Table 4.14. Soil aluminium P in the four Landforms at different levels of fertilizer application after maize had tasselled.

Landform	Rate of fertilizer applied (%)			Landform mean	CV (%)
	0	50	100		
On-station	-------------$\mu g\ P\ g^{-1}$------------------				
Flat bed	5.63	5.53	5. 55	5.74 a	6.66
Ridged bed	5.27	5.20	5.30	5.26 b	
Ethiopian bed	5.50	5.12	5.18	5.27 b	
Cambered bed	5.42	5.29	5.08	5.50 ab	
Fertilizer mean	5.46	5.30	5.46		
On-farm 1					
Flat bed		6.21			3.11
Cambered bed		5.94			
On-farm 2					
Flat bed		5.65			3.32
Cambered bed		5.59			

Landform mean LSD--------------0.29**

Treatment means followed by the same letter within column are not significantly different according to the Duncan's Multiple Range Test.

** Significant P < 0.01

Soil Al-P in the four Landforms after harvesting the maize ranged from 5.31 to 5.88 µg/g for the on-station and 5.93 to 6.88µg/g for the on-farm (Table 4.15). Ethiopian and the

Cambered bed had Al-P content significantly lower than that of the Ridged bed. At the two on-farm sites no significant difference in soil Al-P was observed between the 2 Landforms. During the growth period of maize, the correlation between soil Al-P and dry weight of the maize was not significant.

Table 4.15. Soil aluminium P in the four Landforms at different levels of fertilizer application at maize harvest.

Landform	Rate of fertilizer applied (%)			Landform mean	CV (%)
	0	50	100		
On-station	----------$\mu g\ P\ g^{-1}$	--------------------			
Flat bed	5.44	5.61	5.59	5.55 ab	10.50
Ridged bed	5.88	5.57	5.32	5.59 a	
Ethiopian bed	5.37	5.48	5.42	5.42 b	
Cambered bed	5.43	5.32	5.50	5.41 b	
Fertilizer mean	5.53	5.50	5.45		
On-farm 1					
Flat bed		6.88			4.53
Cambered bed		6.05			
On-farm 2					
Flat bed		5.93			5.52
Cambered bed		5.80			

Landform mean LSD--------------0.14*

Treatment means followed by the same letter at each location are not significantly different according to the Duncan's Multiple Range Test. * Significant at $P < 0.05$

Aluminium bound-P was rarely selected as a predictor to dry weight production. Irrespective of the fertilizer level, landform or maize growth period, the ratio of Ca-P / Al-P was 5 : 1 in both the on-station and on-farm 1 trials. In the on-farm site 2 the ratio was about 6 : 1. This indicates a general balance in these two dominant P-fractions of the Vertisols.

4.7 Iron phosphate

Soil iron phosphate (Fe-P) was the least among the three common inorganic P, viz., Ca-P > Al-P > Fe-P. Before the maize tasselled it ranged between 0.25 and 2.08 µg/g and between 0.52 and 1.62 µg/g in the on-station and on-farm, respectively (Table 4.16). The raised beds had significantly higher Fe-P than the Flat bed at $P < 0.01$. Increasing fertilizer levels resulted in significant decreases in soil Fe-P with a mean drop over the zero application being two and five times lower with respect to the 50 % and the 100 % fertilizer application. With 50 % fertilizer application, the Fe-P content in the CB was lower than the other raised beds. At on-farm 1, soil Fe-P in the Flat bed was significantly lower than that in the Cambered bed. At on-farm 2, however, there was no significant difference between the 2 Landforms. Interaction between the rate of fertilizer and Landforms resulted in significant difference in soil Fe-P content. The iron bound P significantly ($P < 0.05$) correlated with maize dry weight production. The correlation coefficient was negative before maize tasselled but positive after tasselling.

After the maize had tasselled, Fe-P ranged between 0.34 and 0.54 µg/g for the on-station and between 0.79 and 1.26 µg/g for the on-farms (Table 4.17). Differences in the soil Fe-P due to either the Landforms or the fertilizer levels were not significant. The interaction between the Landforms and the rate of fertilizer application did not

Table 4.16. Soil iron P in the four Landforms at different levels of fertilizer application before the maize tasselled.

Landform	Rate of fertilizer applied (%)			Landform mean	CV (%)
	0	50	100		
On-station	----------$\mu g\ P\ g^{-1}$ ------------------				
Flat bed	0.47 c	0.25 c	0.32a	0.35 c	22.31
Ridged bed	1.03 b	1.07 a	0.27a	0.89 b	
Ethiopian bed	2.06a	0.95 ab	0.25a	1.09 a	
Cambered bed	2.08a	0.65 b	0.32a	1.02 ab	
Fertilizer mean	1.49a	0.73 b	0.29 c		
On-farm 1					
Flat bed		0.75 b			4.70
Cambered bed		1.62a			
On-farm 2					
Flat bed		0.70			12.96
Cambered bed		0.52			

Within column mean LSD --------0.37**

Rate of P applied mean LSD ----0.18**

Landform mean LSD--------------0.17**

Treatment means followed by the same letter within column are not significantly different according to the Duncan's Multiple Range Test.

** Significant at $P < 0.01$

result in any significant differences in Fe-P levels. The iron bound P at 100 % rate of fertilizer application was generally higher than that at 50 % rate of application. This trend contrasts the observation for Fe-P content in the soil before the maize tasselled. The Fe-P in the Flat bed was apparently higher than in the Cambered bed but the differences were not significant (Table 4.17). The correlation between Fe-P and dry weight of maize was positive and significant ($P < 0.05$). The Fe-P was selected among the best predictors of dry weight of maize.

Table 4.17. Soil iron P in the four Landforms at different levels of fertilizer application after the maize had tasselled.

Landform	Rate of fertilizer applied (%)			Landform mean	CV (%)
	0	50	100		
On-station	----------μg P g^{-1} ------------------				
Flat bed	0.49	0.39	0.52	0.47	41.24
Ridged bed	0.42	0.43	0.45	0.43	
Ethiopian bed	0.40	0.42	0.52	0.45	
Cambered bed	0.34	0.44	0.54	0.44	
Fertilizer mean	0.41	0.42	0.51		
On-farm 1					
Flat bed		1.26			10.14
Cambered bed		0.83			
On-farm 2					
Flat bed		0.90			18.69
Cambered bed		0.79			

After the maize has been harvested, soil analysis indicated that Fe-P content ranged between 0.20 and 0.33 μg/g and between 0.45 and 0.97 μg/g for the on-station and on-farm, respectively (Table 4.18). Generally, Fe-P content of soil at this stage of the maize growth was lower than Fe-P before and after maize tasselled. The difference in Fe-P as a result of increased fertilizer rate was not significant and so also were the differences due to Landforms. In all the Landforms Fe-P after the maize tasselled and at 100 % rate of fertilizer application was slightly higher than 50 % and 0 %. This observation sharply contrasts the results obtained at the period before maize tasselled (Table 4.16) for the on-station trial. In all the on-farms, differences in Fe-P due to differences in the Landforms was not significant, though in all these sites Fe-P was higher in the Cambered bed than in the Flat bed. There was a progressive and significant drop in Fe-P in the various Landforms as the crop matured. These decreases were associated with the raised beds.

Table 4.18. Soil iron P in the four Landforms at different levels of fertilizer application at the maize harvest.

Landform	Rate of fertilizer applied (%)			Landform mean	CV (%)
	0	50	100		
On-station	---------μg P g^{-1}	---------------------			
Flat bed	0.24	0.28	0.32	0.28	35.22
Ridged bed	0.30	0.33	0.29	0.31	
Ethiopian bed	0.24	0.24	0.25	0.26	
Cambered bed	0.20	0.29	0.32	0.23	
Fertilizer mean	0.24	0.30	0.27		
On-farm 1					
Flat bed		0.67			28.68
Cambered bed		0.97			
On-farm 2					
Flat bed		0.45			19.29
Cambered bed		0.45			

4.8 Soil occluded phosphate

Soil occluded phosphate (occl-P) level before the maize tasselled ranged from 1.22 to 2.72 μg/g for the on-station and much higher (2.84-3.77 μg/g) at the on-farm trials(Table 4.19). Differences in soil occl-P content between the Landforms were not significant. The mean of Flat bed occl-P content was generally higher than that of the raised beds i.e. F > CB > R = EB, this is more discernible with 100 % fertilizer application treatment.

Table 4.19. Soil occluded P in the four Landforms at different levels of fertilizer application before maize tasselled.

Landform	Rate of fertilizer applied (%)			Landform mean	CV (%)
	0	50	100		
On-station	--------μg P g^{-1}	-------------------			
Flat bed	2.50	2.16	1.98	2.21	19.61
Ridged bed	2.72	1.98	1.39	2.03	
Ethiopian bed	2.53	2.58	1.22	2.02	
Cambered bed	2.48	2.48	1.69	2.11	
Fertilizer mean	2.56 a	2.15 b	1.57 c		
On-farm 1					
Flat bed		3.77			5.86
Cambered bed		3.52			
On-farm 2					
Flat bed		3.44			10.27
Cambered bed		2.84			

Rate of fertilizer applied mean LSD ----0.41**

Treatment means followed by the same letter within column are not significantly different according to the Duncan's Multiple Range Test.

** Significant at $P < 0.01$

In both on-farms the difference between the Cambered and the Flat bed was not significant. Differences in occl-P content as a result of three levels of fertilizer application was significant at $P < 0.05$. The trend of occl-P content in soil as a result of fertilizer application in decreasing order was 0 > 50 > 100 %. The correlation between soil occl-P content and dry weight was negative and significant at $P<0.05$.

After the maize had tasselled, soil analysis indicated occl-P content ranged between 2.04 and 2.89 μg/g for the on-station and 3.6 - 4.90 μg/g for the on-farm (Table 4.20). The concentration is thus higher in the soil than before the maize tasselled. The differences in soil occl-P in the Landforms were not significant at all the sites. Similarly, the three levels of fertilizer application also gave no significant differences in occl-P. In on-farm 1 though the Flat bed was higher in occl-P than Cambered, the difference between them was not significant, in on-farm 2 the trend is reversed (Table 4.20). At both tasselling and harvesting, the correlation between the various dry matter yield and the occl-P was not significant.

Table 4.20. Soil occluded P in the four landforms at different levels of fertilizer application after maize tasselled.

Landform	Rate of fertilizer applied (%)			Landform mean	CV (%)
	0	50	100		
On-station	------------	$\mu g\ P\ g^{-1}$	-------------------		
Flat bed	2.36	2.59	2.04	2.33	16.83
Ridged bed	2.89	2.75	2.55	2.65	
Ethiopian bed	2.39	2.34	2.84	2.34	
Cambered bed	2.37	2.30	2.20	2.29	
Fertilizer mean	2.50	2.49	2.27		
On-farm 1					
Flat bed		4.90			10.28
Cambered bed		3.77			
On-farm 2					
Flat bed		3.60			11.76
Cambered bed		3.79			

After the maize has been harvested, occl-P in the soil ranged between 1.86 and 2.49 μg/g for the on-station and from 2.9 to 4.27 μg/g for the on-farm (Table 4.21). There were statistically no significant difference between the Landforms at all the experimental sites.

Differences in occl-P levels as a result of different fertilizer rates were also not significant but at 100 % application a decreasing trend of EB > R > CB was observed for the raised beds. Generally, increasing levels of fertilizer application resulted in the reduction of soil occl-P content but not significantly. Whereas in on-farm 1 occl-P levels in Cambered bed was significantly lower than that of the Flat bed, in on-farm 2 both Landforms had equal levels (Table 4.21), thus like Fe-P indicating some of the inherent differences between the two on-farm site.

Table 4.21. Soil occluded P in the four Landforms at different levels of fertilizer application at maize harvest.

Landform	Rate of fertilizer applied (%)			Landform mean	CV (%)
	0	50	100		
On-station	---------$\mu g\ P\ g^{-1}$---------------------				
Flat bed	2.49	2.30	1.94	2.25	28.98
Ridged bed	2.06	2.29	2.10	2.14	
Ethiopian bed	2.41	2.32	2.13	2.29	
Cambered bed	2.04	2.00	1.86	1.96	
Fertilizer mean	2.25	2.22	2.01		
On-farm 1					
Flat bed		4.27a			4.41
Cambered bed		2.90 b			
On-farm 2					
Flat bed		4.10			4.75
Cambered bed		4.10			

$P < 0.05$

4.9 Plant analysis

4.9.1 Phosphorus concentration in maize leaf at tasselling

The mean range in phosphorus concentration in the maize leaf at tasselling was between 0.32 and 0.46 % for the on-station and from 0.28 to 0.37 % for the on-farms (Table 4.22). At 0 % rate of fertilizer application, P concentration in the leaf on the Flat bed was equal to that of the Ridge bed and both were higher than that of the Ethiopian and the Cambered beds.

Table 4.22. Concentration of P in maize leaf from the four Landforms with different levels of fertilizer application at tasselling.

Landform	Rate of fertilizer applied (%)			Landform mean	CV (%)
	0	50	100		
On-station	-----------% P --------------------				
Flat bed	0.46	0.39	0.36	0.40a	
Ridged bed	0.46	0.39	0.36	0.40a	
Ethiopian bed	0.40	0.34	0.35	0.36ab	
Cambered bed	0.39	0.32	0.32	0.34 b	
Fertilizer mean	0.43 a	0.36 b	0.35 b		
On-farm 1					
Flat bed		0.28 b			
Cambered bed		0.37a			
On-farm 2					
Flat bed		0.31			
Cambered bed		0.31			

Rate of fertilizer applied mean LSD ----0.03**

Landform mean LSD--------------0.04**

Treatment means followed by the same letter within column are not significantly different according to the Duncan's Multiple Range Test.

** Significant $P < 0.01$

On all the Landforms, application of fertilizer caused decrease in leaf P concentration. The mean leaf P concentration of maize on the CB was significantly lower than those of the Flat and the Ridged. Whereas at on-farm 1, the difference in leaf P between CB and F was significant, it was not so in on-farm 2 (Table 4.22).

4.9.2 Dry matter yield of maize leaf at tasselling

The dry matter yield of maize leaf increased significantly ($P < 0.01$) with increasing rate of fertilizer application (Table 4.23). Before the maize tasselled, the rate of fertilizer applied, organic-P, iron-P, and occl-P significantly correlated with leaf dry weight(Table 4.24). While the correlation was significantly positive with the rate of fertilizer, it was negative with the org-P, Fe-P and occl-P. The Landform, rate of fertilizer, available P and organic P accounted for 60 % of the variations in leaf dry weight.

Generally, the dry weight of leaf was higher on the raised beds than the Flat bed. The Cambered bed gave the highest dry matter yield followed by the Ridged, the Ethiopian and the Flat bed in that order. There was no significant difference between the Ridged and the Ethiopian bed, however, both were significantly ($P < 0.05$) higher than the Flat bed. At 0 % rate of fertilizer application, leaf dry matter yield decreased in the order of CB > EB > R > F. At 50% the trend of dry matter production was CB > R > EB > F and the corresponding yield increases were 78 %, 42 % and 11 % over the Flat bed respectively. Generally, the dry leaf yield increases were 64 % for CB, 44 % for R and 34 % for EB over the Flat bed. In both on-farm 1 and 2, dry matter yield of maize leaf on the Cambered bed

Table 4.23. Dry matter weight (g) of leaf from the four Landforms with different levels of fertilizer application at maize tasselling.

Landform	Rate of fertilizer applied (%)			Landform mean	CV (%)
	0	50	100		
On-station	---------g leaf^{-1}	--------------	--------------		
Flat bed	7.08 c	12.64 d	16.98 c	12.23 c	14.15
Ridged bed	9.27 b	17.94 b	25.62 ab	17.61 b	
Ethiopian bed	9.85 ab	14.02 c	25.49 b	16.45 b	
Cambered bed	10.88 a	22.46a	26.87 a	20.07 a	
Fertilizer mean	9.27 c	16.77 b	23.74 a		
On-farm 1					
Flat bed		27.04 b			7.66
Cambered bed		28.56a			
On-farm 2					
Flat bed		22.81 b			6.33
Cambered bed		29.48a			

Within column mean LSD --------1.36**

Rate of fertilizer applied mean LSD ----0.68**

Landform mean LSD--------------0.88**

Treatment means followed by the same letter within column are not significantly different according to the Duncan's Multiple Range Test.

** Significant $P < 0.01$

was significantly higher ($P < 0.05$) than the Flat bed (Table 4.23). After tasselling, only available P, Fe-P and Ca-P significantly correlated with the leaf dry weight at $P < 0.05$ (Table 4.25). These three predictor variables in addition to the Landforms and organic-P accounted for 60.5 and 67.3 % of the variations in leaf dry weight before and after tasselling respectively (Table 4.26 and 4.27).

Table 4.24. Correlation between dry weight of maize and soil variables before the maize tasselled.

	Leaf	Stubble	Root	Cob	Grain
2. Rate of P	0.871*	0.809*	0.864*	0.741*	0.663*
3. Total P	-0.146	-0.065	-0.273	-0.246	-0.232
4. Avail-P	0.141	0.348*	0.388*	0.365*	0.352*
5. Org-P	-0.598*	-0.515*	-0.551*	-0.543*	-0.533*
6. Ca-P	-0.269	-0.277	-0.356*	-0.452*	-0.543*
6. Al-P	-0.123	-0.107	-0.100	-0.103	-0.139
7. Fe-P	-0.557*	-0.551*	-0.575*	-0.469*	-0.407*
8. Occl-P	-0.750*	-0.715*	-0.609*	-0.299*	-0.509*

* Significant at $P < 0.05$

Table 4.25. Correlation between dry weight of maize and soil variables after the maize tasselled.

	Leaf	Stubble	Root	Cob	Grain
2. Rate of P	0.221	0.190	0.206	0.197	0.135
3. Total P	0.017	0.120	0.136	0.125	0.063
4. Avail-P	0.345*	0.349*	0.441*	0.386*	0.377*
5. Org-P	-0.206	0.033	0.030	0.040	0.102
6. Ca-P	0.373*	0.422*	0.486*	0.631*	0.656*
6. Al-P	0.145	0.144	0.252	0.120	0.207
7. Fe-P	0.717*	0.608*	0.643*	0.579*	0.510*
8. Occl-P	-0.253	-0.046	-0.032	-0.113	-0.112

* Significant at $P < 0.05$

Table 4.26. Best subset regression of maize dry weight on nine predictor variables before the maize tasselled.

Maize part	Best subset of selected variables	R^2 for the selected variables	R^2 for all the nine variables
1. Leaf	landform, rate of P, available P, org-P,	60.5	64.1
2. Stubble	landform, rate of P, available P, org-P, Ca-P, occl-P	78.8	79.5
3. Root	rate of P, available P, org-P, Fe-P	66.3	67.0
4. Cob	landform, rate of P, available P, org-P, Ca-P, occl-P	59.5	60.9
5. Grain	rate of P, available P, org-P, Fe-P, Ca-P	49.9	50.7

4.9.3 Phosphorus uptake of maize leaf at tasselling

The differences between the four Landforms with respect to P uptake were statistically significant ($P < 0.05$) (Table 4.28). Uptake of P on the raised beds was higher than uptake on the Flat bed. Addition of fertilizer resulted in significant increased in P uptake on all the Landforms. The percentage increase of P uptake due to 50 % and 100 % fertilizer application over that of 0 % was 54 and 106 % respectively. At 0 % and 50 % fertilizer rate, there was a decreasing trend in P uptake: CB > R > EB > F; and R > CB > EB = F respectively. At 100 % fertilizer rate of application the raised beds had significantly higher ($P < 0.01$) P uptake than that of the Flat bed. Similar to the on-station site,

Table 4.27. Best subset regression of maize dry weight on nine predictor variables after the maize tasselled.

Maize part	Best subset of predictor variables	R^2 for selected variables	R^2 for all the nine variables
1. Leaf	landform, available P, org-P, Fe-P, Ca-P	67.3	67.7
2. Stubble	landform, available P, Fe-P, rate of P, occl-P	40.5	41.3
3. Root	landform, available P, Fe-P, occl-P, Al-P	65.4	66.2
4. Cob	landform, rate of P, available P, Fe-P	73.0	73.6
5. Grain	rate of P, available P, org-P, Fe-P	54.6	54.7

P uptake on the Cambered bed in both on-farm 1 and 2 was significantly higher than uptake on Flat bed in both on-farms. Before the maize tasselled, P uptake in leaf correlated significantly with the P rate, organic P, Fe-P and occluded-P. After tasselling only Fe-P and available P correlated significantly with leaf P uptake (Tables 4.28 and 4.29) suggesting that Fe-P or P from this fraction plays an important role in the P uptake processes in the maize plant.

Table 4.28. Phosphorus uptake of maize leaf on the four Landforms with different levels of fertilizer application at the tasselling stage.

Landform	Rate of fertilizer applied (%)			Landform mean	CV (%)
	0	50	100		
On-station	-----------g plot^{-1}	--------------			
Flat bed	3.72 a	4.90 b	7.07 b	5.23 c	12.68
Ridged bed	4.15 a	7.64 a	9.12 a	6.98 a	
Ethiopian bed	3.93 a	4.77 b	8.83 a	5.84 bc	
Cambered bed	4.24 a	7.28 a	8.03 ab	6.52 ab	
Fertilizer mean	4.01 c	6.16 b	8.26 a		
On-farm 1					
Flat bed		7.71 b			5.93
Cambered bed		10.46a			
On-farm 2					
Flat bed		7.13 b			6.33
Cambered bed		8.87a			

Within column mean LSD --------1.54**

Rate of P applied mean LSD ----0.77**

Landform mean LSD-------------1.10*

Treatment means followed by the same letter within column are not significantly different according to the Duncan's Multiple Range Test.

* Significant $P < 0.05$, ** Significant $P < 0.01$

4.10 Phosphorus concentration in maize stubble

Table 4.31 shows phosphorus concentration in maize stubble. It ranged from 0.09 to 0.29 % for the on-station and is generally lower (0.1 to 0.19 %) for the on-farm trials. Statistically, no significant difference was found among the four Landforms. However, phosphorus concentration reduced significantly when the fertilizer level was raised progressively from 0 to 100 % on the raised beds.

Table 4.29. Correlation between P uptake of maize and soil variables before the maize tasselled.

	Leaf	Stubble	Root	Cob	Grain
2. Rate of P	0.817*	0.328*	0.260	0.476*	0.653*
3. Total P	-0.039	-0.160	-0.074	-0.008	-0.225
4. Avail-P	0.167	0.175	0.216*	0.353*	0.333*
5. Org-P	-0.452*	-0.277	-0.207	-0.188	-0.466*
6. Ca-P	-0.124	-0.250	-0.200	-0.416*	-0.606*
6. Al-P	-0.047	-0.181	-0.087	-0.003	-0.044
7. Fe-P	-0.550*	-0.133	-0.122	-0.392*	-0.424*
8. Occl-P	-0.713*	-0.298*	-0.223*	-0.299*	-0.414*

* Significant at P < 0.05

Table 4.30. Correlation between P uptake of maize and soil variables after the maize tasselled.

	Leaf	Stubble	Root	Cob	Grain
2. Rate of P	0.180	0.080	0.017	0.132	0.221
3. Total P	-0.001	-0.064	-0.062	0.041	0.030
4. Avail-P	0.372*	0.011	0.002	0.306*	0.404*
5. Org-P	-0.219	-0.088	-0.070	0.108	0.176
6. Ca-P	0.272	0.260	0.276	0.542*	0.616*
6. Al-P	0.063	0.119	0.118	0.322*	0.228
7. Fe-P	0.614*	0.170	0.172	0.419*	0.539*
8. Occl-P	-0.146	-0.080	-0.085	-0.075	-0.118

* Significant at P < 0.05

The reduction in P concentration due to increase in fertilizer level from 50 % to 100 % was not significant. In all the Landforms the P concentration in the stubble decreased in the order F > R > CB > EB. In both on-farms P concentration in the stubble on the Cambered bed was not significantly different from that on the Flat bed.

Table 4.31. Phosphorus concentration in maize stubble for the four Landforms with different levels of fertilizer application at maize harvest.

Landform	Rate of fertilizer applied (%)			Landform mean	CV (%)
	0	50	100		
On-station	-----------% P ---------------------				
Flat bed	0.29	0.19	0.11	0.20	23.23
Ridged bed	0.27	0.13	0.10	0.17	
Ethiopian bed	0.22	0.14	0.09	0.15	
Cambered bed	0.27	0.11	0.10	0.16	
Fertilizer mean	0.26 a	0.14 b	0.099 b		
On-farm 1					
Flat bed		0.10			13.33
Cambered bed		0.19			
On-farm 2					
Flat bed		0.10			12.00
Cambered bed		0.16			

Rate of fertilizer applied mean LSD ----0.065**

Treatment means followed by the same letter are not significantly different according to the Duncan's Multiple Range Test. ** Significant $P < 0.01$

significant increase in the stubble production. The treatment effect of fertilizer application and Landforms was significant. At 0 % rate of fertilizer application, the trend in the stubble weight

4.10.1 Dry matter yield of stubble at harvest

Differences in dry weight of stubble on different landforms was statistically significant ($P < 0.05$). The yield of stubble on either the Ridged or the Cambered bed was almost two times that of the Flat bed (Table 4.32). Also, increase in the rate of fertilizer application resulted in significant increase in stover production.

Table 4.32. Dry matter weight (g) of maize stubble for the four Landforms with different levels of fertilizer application at harvest.

Landform	Rate of fertilizer applied (%)			Landform mean	CV (%)
	0	50	100		
On-station	---------------- g $Plant^{-1}$--------				
Flat bed	6.58 b	14.39 c	17.55 d	12.84 d	3.58
Ridged bed	8.41a	26.45a	34.13a	22.99a	
Ethiopian bed	8.49a	25.07 b	24.12 c	15.93 c	
Cambered bed	8.64a	26.87a	26.98 b	20.83 b	
Fertilizer mean	8.03 c	20.70 b	25.72a		
On-farm 1					
Flat bed		24.11a			2.03
Cambered bed		25.44a			
On-farm 2					
Flat bed		15.34 b			3.15
Cambered bed		20.37a			

Within column mean LSD --------1.28**

Rate of P applied mean LSD ----0.64**

Landform mean LSD--------------0.94**

Treatment means followed by the same letter within column are not significantly different according to the Duncan's Multiple Range Test.

** Significant $P < 0.01$

Interaction between rate of fertilizer application and Landforms resulted in significant differences in stover yield. At 0 % of fertilizer application, the trend in the stover weight decreased from the Cambered to the Flat bed i.e CB > EB = R > F. At 50 % rate of fertilizer application, stubble production on the Landforms had a decreasing trend of CB = R > EB > F. The yield on the Cambered bed was equal at 50 % and 100 % rate, but the latter caused a 27 % yield increase on the Ridged over the Cambered bed. In on-farm 2, dry weight of stubble on the Cambered bed was significantly higher ($P < 0.05$) than on the Flat bed while the difference between the two Landforms was not significant in on-farm 1.

Before the maize tasselled, dry matter weight of the stubble significantly correlated ($P < 0.05$) with rate of fertilizer application, available P, organic P, Fe-P and occl-P (Table 4.24) which accounted for 78.8 % of the variations in the stubble production. At tasselling, the stubble weight significantly correlated with only available P, Fe-P and Ca-P. These parameters accounted for only 40.5 % of the variations in the stubble production, (Table 4.29).

4.10.2 Phosphorus uptake by maize stubble at harvest

Differences in uptake of phosphorus by maize stubble on the four landforms were statistically significant (Table 4.33). At both 50 % and 100 % fertilizer application, P uptake was highest on the Cambered bed, followed by the Ridged bed with the Ethiopian and the Flat bed following in that order. On the Cambered bed, P uptake was more than twice that of the Flat bed. Increased rate of fertilizer application brought about significant

Table 4.33. Phosphorus uptake by maize stubble for the four Landforms with different levels of fertilizer application at harvest.

Landform	Rate of P fertilizer (%)			Landform mean	CV (%)
	0	50	100		
On-station	--------------g plot^{-1}--------------				
Flat bed	1.82 a	1.21 c	2.07 c	1.70 c	23.19
Ridged bed	2.84 a	3.48 ab	3.30 b	3.02 ab	
Ethiopian bed	1.91 a	2.34 bc	2.10 c	2.08 bc	
Cambered bed	2.50 a	3.88 a	4.69 a	3.69 a	
Fertilizer mean	2.13 b	2.70 ab	3.04 a		
On-farm 1					
Flat bed		2.57 b			4.44
Cambered bed		4.68a			
On-farm 2					
Flat bed		1.55 b			4.72
Cambered bed		3.17a			

Within column mean LSD --------1.20**

Rate of fertilizer applied mean LSD ----0.60**

Landform mean LSD--------------0.83**

Treatment means followed by the same letter within column are not significantly different according to the Duncan's Multiple Range Test.

** Significant $P < 0.01$

increase in P uptake. There was significant interaction between fertilizer rate and Landforms. At both 0 and 50 % levels of fertilizer, the order of P uptake was decreased as CB = R > EB = F. With fertilizer application, P uptake on the Cambered was superior to all other landforms. Phosphorus uptake on the Cambered bed at both on-farms was also significantly higher than that of the Flat bed.

4.11 Phosphorus concentration in maize root at harvest

Phosphorus concentration in maize root is reported in Table 4.34. It ranged between 0.057 and 0.098 %. Differences in concentration of P in maize root on the Landforms at both the on-station and at the on-farm trials were not significant. Addition of fertilizer resulted in significant decrease in P concentration, particularly on the Flat and the Ethiopian bed but raising the level from 50 % to 100 % did not show any significant difference in P concentration. At 0 % rate of fertilizer application, P concentration in the root on various Landforms was in the decreasing order of F = R > EB = CB.

Table 4.34. Phosphorus concentration in maize root for the four Landforms with different levels of fertilizer application at harvest.

Landform	Rate of fertilizer applied (%)			Landform mean	CV (%)
	0	50	100		
On-station	---------% P	-----------------------			
Flat bed	0.098	0.058	0.062	0.072	21.90
Ridged bed	0.096	0.074	0.068	0.079	
Ethiopian bed	0.084	0.057	0.067	0.069	
Cambered bed	0.085	0.081	0.078	0.081	
Fertilizer mean	0.091 a	0.067 b	0.069 b		
On-farm 1					
Flat bed		0.069			3.09
Cambered bed		0.071			
On-farm 2					
Flat bed		0.087			2.9
Cambered bed		0.076			

Rate of fertilizer applied mean LSD ----0.009*

Treatment means followed by the same letter are not significantly different according to the Duncan's Multiple Range Test. * Significant at $P < 0.05$

4.11.1 Dry matter yield of maize root at harvest

Differences between dry root yield on the four Landforms were significant (Table 4.35). The superiority of the Cambered bed in improving the root yield is clearly demonstrated by the significant 50 % yield increases without any fertilizer application. The order of root yield in the Landforms is CB > R = EB > F.

Table 4.35. Dry weight (g) of root of maize for the four Landforms with different levels of fertilizer application at harvest.

Landform	Rate of fertilizer applied (%)			Landform mean	CV (%)
	0	50	100		
On-station	-------------- g Plant^{-1}	------------			
Flat bed	4.011 c	7.897 b	8.28 c	6.659 c	12.76
Ridge bed	4.497 b	8.490a	8.807 b	7.264 b	
Ethiopian bed	4.349 bc	8.013 b	8.369 c	6.910 c	
Cambered bed	6.001a	8.635a	9.558a	8.064a	
Fertilizer mean	4.714 c	8.259 b	8.701a		
On-farm 1					
Flat bed		7.748 b			11.49
Cambered bed		8.785a			
On-farm 2					
Flat bed		9.409a			11.77
Cambered bed		9.776a			

Within column mean LSD ---------------0.369**

Rate of fertilizer applied mean LSD ----0.168**

Landform mean LSD---------------------0.292**

Treatment means followed by the same letter within column are not significantly different according to the Duncan's Multiple Range Test. ** Significant at $P < 0.01$

This indicates the benefit of the raised beds over the Flat bed for root development. Increased fertilizer application resulted in significant increase in dry root weight in all the Landforms. Treatment effect on root dry matter production was significant ($P < 0.01$). Apart from the total P and Al-P, correlation between root dry weight and the soil variables before the maize tasselled was significant and generally negative (Table 4.24). After the maize had tasselled, only available P, Fe-P and Ca-P significantly and positively correlated with root weight (Table 4.25).

4.11.2 Phosphorus uptake by maize root at harvest

There were no significant differences among P uptake on the different Landforms (Table 4.36). It is apparent from Table 4.36 that the Cambered bed did better than all the other Landforms. Addition of fertilizer resulted in significant ($P < 0.05$) increase in P uptake of roots. On both Cambered and Ridged beds the 50 % fertilizer rate gave a higher P uptake than the 100 %. The reverse is true on the Ethiopian and Flat beds, though these differences were not significant. The trends in the root uptake of P on the Landforms at 50% and 100 % rate are similar to the corresponding trends in the root performance; CB > R > EB> F (Tables 4.35 and 4.36). Phosphorus uptake by the roots on the Cambered bed in on-farm 1 was significantly ($P < 0.05$) higher than the uptake on the Flat bed. No such differences in on-farm 2 were observed. The root uptake did not significantly correlate with any of the soil variables (Tables 4.26 and 4.27).

Table 4.36. Phosphorus uptake of maize roots from four landforms with different levels of fertilizer application at harvest.

Landform	Rate of fertilizer applied (%)			Landform mean	CV (%)
	0	50	100		
On-station	-------------g plot^{-1}--------------				
Flat bed	0.385	0.429	0.503	0.439	23.31
Ridged bed	0.524	0.686	0.592	0.600	
Ethiopian bed	0.476	0.457	0.564	0.499	
Cambered bed	0.478	0.774	0.723	0.658	
Fertilizer mean	0.466 b	0.586 a	0.596 a		
On-farm 1					
Flat bed		0.554 b			12.72
Cambered bed		0.885a			
On-farm 2					
Flat bed		1.007			10.71
Cambered bed		1.046			

Rate of fertilizer applied mean LSD ----0.107*

Treatment means followed by the same letter are not significantly different according to the Duncan's Multiple Range Test. * Significant at $P < 0.05$

4.12 Phosphorus concentration in maize cob at harvest

As shown in Table 4.37, phosphorus concentration in the maize cob ranged between 0.083 and 0.111 % for the on-station and between 0.087 and 0.101 % for the on-farm trials. The P concentration in maize cob showed no significant differences on the Landforms. Similarly, increased levels of fertilizer did not significantly influence P concentration in the cob. Similar observation was made in both on-farm 1 and 2.

Table 4.37. Phosphorus concentration in maize cob for the four Landforms with different levels of fertilizer application at maize harvest.

Landform	Rate of P fertilizer applied (%)			Landform mean	CV (%)
	0	50	100		
On-station	---------------	% P	---------------		
Flat bed	0.109	0.111	0.098	0.106	16.20
Ridged bed	0.096	0.098	0.091	0.095	
Ethiopian bed	0.104	0.106	0.083	0.098	
Cambered bed	0.087	0.100	0.094	0.094	
Fertilizer mean	0.099	0.104	0.091		
On-farm 1					
Flat bed		0.089			20.01
Cambered bed		0.101			
On-farm 2					
Flat bed		0.087			17.40
Cambered bed		0.090			

4.12.1 Dry weight of maize cob at harvest

Generally, there was a decreasing trend of the dry cob weight on the Landforms i.e. CB > EB = R > F at $P < 0.05$ (Table 4.38). The dry cob weight on the raised beds were significantly higher than that of the Flat bed. Increased level of fertilizer application resulted in significant increase in the cob yield. There were significant differences in cob weight as a result of interaction between Landform and different rate of fertilizer application. Cob yield on the Cambered bed at 50 % rate of fertilizer was much higher than at 100 % rate but the reverse was true for the Ridged and the Flat beds. On the Ethiopian bed, yield at 50 % was equal to yield at 100 % fertilisation while on the Flat bed 100 % fertilizer rate out yielded 50 % rate. In both on-farm 1 and 2 no significant difference in dry

Table 4.38. Dry matter weight (g) of maize cob for the four Landforms with different levels of fertilizer application at harvest.

Landform	Rate of fertilizer applied (%)			Landform mean	CV (%)
	0	50	100		
On-station	------------------ g cob $^{-1}$ ----------------				
Flat bed	4.504 c	6.19 d	7.21 d	5.97 c	12.41
Ridged bed	5.05 b	6.85 c	8.65 b	6.85 b	
Ethiopian bed	5.21 b	7.79 b	7.87 c	6.96 b	
Cambered bed	5.94 a	10.10a	8.99a	8.34a	
Fertilizer mean	5.18 c	7.73 b	8.18a		
On-farm 1					
Flat bed		12.19			14.14
Cambered bed		13.89			
On-farm 2					
Flat bed		8.57			14.99
Cambered bed		9.58			

Within column mean LSD --------0.248**

Rate of fertilizer applied mean LSD ----0.106**

Landform mean LSD--------------0.143**

Treatment means followed by the same letter within column are not significantly different according to the Duncan's Multiple Range Test. ** Significant at $P < 0.01$

Before the maize tasselled, all the soil variables except total P and Al-P significantly correlated with cob weight. These variables accounted for 59.5 % of variations in cob yield (Table 4.26). At tasselling, available P, Fe-P and Ca-P significantly correlated with cob yield. Together with Landforms and rate of fertilizer applied, these five variables accounted for 73 % of the variation in cob yield (Table 4.29).

4.12.2 Phosphorus uptake by maize cob at harvest

The differences in phosphorus uptake by cobs on the Landforms were not significant (Table 4.39). Increased fertilizer level from 50 to 100 % did not result in a significant increase in P uptake. However, the addition of fertilizer resulted in significant increase in the P uptake. For example at 50 % fertilisation, the trend of P uptake decreased as follows CB > EB > R > F (Table 4.39).

Table 4.39. Phosphorus uptake by maize cob for the four Landforms with different levels of fertilizer application at harvest.

Landform	Rate of fertilizer applied (%)			Landform mean	CV (%)
	0	50	100		
On-station	------------g $plot^{-1}$------------				
Flat bed	0.493	0.660	0.715	0.623	12.41
Ridged bed	0.483	0.664	0.841	0.663	
Ethiopian bed	0.529	0.683	0.653	0.622	
Cambered bed	0.517	0.817	0.816	0.716	
Fertilizer mean	0.505 b	0.706 a	0.756 a		
On-farm 1					
Flat bed		1.084 b			13.82
Cambered bed		1.403a			
On-farm 2					
Flat bed		0.758			14.93
Cambered bed		0.863			

Rate of fertilizer applied mean LSD ----0.130*

Treatment means followed by the same letter are not significantly different according to the Duncan's Multiple Range Test. * Significant at $P < 0.05$

In on-farm 1, P uptake by the maize cob on the Cambered bed was significantly higher than P uptake on the Flat bed, but in on-farm 2 the differences were not significant. P uptake by the cob consistently correlated with available P, Ca-P and Fe-P.(Tables 4.28 and 4.29).

4.13 Grain yield at harvest

Maize grain yield was highest on the Cambered bed and least on the Flat bed (Table 4.40). There were significant differences ($P < 0.05$) in the yield between the four Landforms and a decreasing trend of CB > EB ≥ R > F was observed. Addition of fertilizer resulted in significant increase in grain weight. The 100 % rate of fertilizer application gave the highest grain yield followed by the 50 % fertilizer rate in all the Landforms except the Cambered bed which gave the highest yield at 50 % fertilizer rate. The differences between these two rates were however not significant. At 0 % rate, grain yield on the four Landforms were of decreasing order EB = CB > R = F. At 50 % fertilizer application, a decreasing trend of CB > EB > R > F was observed. The CB at 50% fertilizer application out-yielded the 100 % by 21 %. Grain yield from the Cambered bed in both on-farm 1 and 2 was significantly ($P < 0.05$) higher than that from the Flat bed (Table 4.40). Yield was generally higher at on-farm 1 than on-farm 2. Except for total P and Al-P, the

Table 4.40. Dry weight (g) of maize grains per plant for the four Landforms with different levels of fertilizer application at harvest.

Landform	Rate of fertilizer applied (%)			Landform mean	CV (%)
	0	50	100		
On-station	---------- g Plant^{-1}	----------	----------		
Flat bed	16.879 b	27.294 c	32.457 b	25.577 c	8.09
Ridged bed	17.647 b	28.436 bc	33.146 b	26.409 c	
Ethiopian bed	24.279a	31.036 b	34.036 b	29.483 b	
Cambered bed	24.099a	47.901 a	39.452 a	37.141 a	
Fertilizer mean	20.743 b	33.667 a	34.548 a		
On-farm 1					
Flat bed		67.802 b			6.74
Cambered bed		80.784a			
On-farm 2					
Flat bed		21.267 b			11.68
Cambered bed		24.943a			

Within column mean LSD ---------3.544**

Rate of fertilizer applied mean LSD ----1.521**

Landform mean LSD--------------2.635**

Treatment means followed by the same letter with column are not significantly different according to the Duncan's Multiple Range Test.

** Significant at $P < 0.01$

rest of the soil variables significantly correlated with the grain yield (Table 4.24). After maize had tasselled, the available P, Fe-P and Ca-P significantly correlated with grain yield ($P < 0.05$). Only between 49.9 and 54.6 % of the variations in grain yield could be explained by the selected soil predictor variables (Tables 4.26 and 4.27).

4.13.1 Phosphorus concentration in maize grain at harvest

Phosphorus concentration in the maize grain ranged between 0.256 and 0.339 % for the on-station and from 0.247 to 0.275 % for the on-farm trials as shown in Table 4.41. The difference in grain P concentration of the four Landforms were not significant. However, differences in grain P concentration at different fertilizer application levels were significant.

Table 4.41. Phosphorus concentration in maize grain on the four Landforms at different levels of fertilizer application at harvest.

Landform	Rate of fertilizer applied (%)			Landform mean	CV (%)
	0	50	100		
On-station	------------% P	----------------------			
Flat bed	0.287	0.292	0.270	0.283	12.82
Ridged bed	0.278	0.280	0.257	0.272	
Ethiopian bed	0.339	0.320	0.261	0.307	
Cambered bed	0.276	0.267	0.256	0.266	
Fertilizer mean	0.295 a	0.290 a	0.261 b		
On-farm 1					
Flat bed		0.274			8.01
Cambered bed		0.275			
On-farm 2					
Flat bed		0.247			6.38
Cambered bed		0.247			

Rate of fertilizer applied mean LSD ----0.023*

Treatment means followed by the same letter are not significantly different according to the Duncan's Multiple Range Test. * Significant at $P < 0.05$

4.13.2 Phosphorus uptake by maize grains at harvest

Uptake of P in the maize grain from the Cambered bed was significantly higher than those of the rest, which were not significantly different from each other. Addition of fertilizer resulted in significant increase in P uptake by grains but the corresponding uptake by increasing fertilizer level to 100 % was not significant. There was a decrease in P uptake on both EB and CB and an increase in R and F as fertilizer rate was raised from 50 % to 100 % (Table 4.42).

Table 4.42. Phosphorus uptake in maize grain for the four Landforms at different levels of fertilizer application at harvest.

Landform	Rate of fertilizer applied (%)			Landform mean	CV (%)
	0	50	100		
On-station	------------------g plot^{-1}------------				
Flat bed	4.885 c	9.692 bc	11.169 b	8.582 b	15.21
Ridged bed	5.062 bc	8.758 c	11.046 b	8.289 b	
Ethiopian bed	6.945 a	10.801 b	8.022 c	8.888 b	
Cambered bed	8.022 a	14.176 a	12.609 a	11.602 a	
Fertilizer mean	6.228 b	10.857 a	10.936 a		
On-farm 1					
Flat bed		18.578			6.73
Cambered bed		22.216			
On-farm 2					
Flat bed		16.565			8.75
Cambered bed		17.044			

Within column mean LSD --------1.98*

Rate of fertilizer applied mean LSD ----1.37*

Landform mean LSD--------------1.73*

Treatment means followed by the same letter with column are not significantly different according to the Duncan's Multiple Range Test. * Significant at $P < 0.05$

Concentration of P in grain was influenced significantly by rate of fertilizer and Landform interaction. The highest uptake occurred on the Cambered with 50 % fertilizer. Differences in P uptake of maize grain on the two Landforms at both on-farm 1 and 2 were not statistically significant. Apart from the soil total P and Al-P, there was significant correlation between P uptake by the grain and the rest of the soil variables (Tables 4.26 and 4.27).

CHAPTER FIVE

5 DISCUSSION

The objectives of landshaping technology on Vertisols are to shed off excess water from the soil during heavy rains and also to conserve enough water for the long term cultivation of crops. Phosphorus is deficient in the Vertisols (Finck and Venkateswarlu, 1982). There is the need, to determine suitable P-dose to ensure agronomic efficiency.

5.1 General soil characteristics

The major differences observed between the on-station and on-farm soils were in organic carbon, total nitrogen and organic P content. These differences could be attributed to the cropping history of the experimental sites. While the on-farm sites were fallow lands, the on-station site was under constant cultivation. This could have resulted in higher organic matter accumulation at the on-farm sites compared to the on-station site. This was reflected in higher soil organic carbon at the on-farm compared to on-station soils.

5.2 Dry matter yield, rate of fertilizer application and Landforms

Generally, dry matter yield of maize (leaf, stubble, root, cob and grain) responded significantly to the fertilizer application (Tables 4.23, 4.32, 4.35, 4.38 and 4.40). Soil analysis at the start of experiment indicated a low level of available P, averaging 3.03 µg/g. Acquaye and Owusu-Bennoah (1989) reported a range of 0.1 -3.5 µg/g in the Vertisol of Accra plains and 2.0 - 10.0 ug/g was reported for some Indian Vertisols (Katyal, 1978). Tandon and Kanwar (1984) contended that in India, a soil is considered deficient if it contains less than 5.0 µg/g using Olsen's $NaHCO_3$ method.

The results showed that increasing fertilizer levels brought a corresponding significant increase in dry weight of maize. In most cases more than 60 % increase in weight was observed as a result of fertilizer application. For instance addition of fertilizer raised grain dry weight from 20.74 g/plant to 33.67 g/plant and to 34.55 g/plant (Table 4.40) (1.29 ton/ha to 2.10 ton/ha and finally to 2.23 ton/ha) respectively. This might have resulted from increased phosphate availability to the maize crop as a result of fertilizer addition to the soil.

Relatively high levels of soil available P due to fertilizer application (Table 4.7) resulted in the maize plant obtaining adequate level of P for optimum growth resulting in high biomass production. The rate of fertilizer application was significantly correlated to P uptake before the maize tasselled. On the other hand the correlation between the rate of fertilizer applied and P uptake after tasselling was not significant. This may be because increases in applied fertilizer may not have necessarily led to increases in P uptake since several factors which influence the availability and uptake of P may be operative at that stage of growth. Le Mare (1987) and Ahmad (1989) supported this view by citing factors such as soil moisture, pH, P-sorption, etc. as influencing phosphate availability to crops. Contrary to expectation, soil available P at 100 % fertilizer application was lower than at 50 % application (Table 4.7).

This could be explained by the higher P uptake by the maize plant at 100 % fertilizer application compared to the 50 % application (Table 4.28).

Generally, the raised beds (namely Ridged, Ethiopian and Cambered bed) significantly outperformed the Flat bed in terms of dry matter production. For instance, grain yield on the Flat bed was 1.59 tons/ha while that of the raised bed was on the average 2.32 tons/ha. Dua-Yentumi *et al.* (1992 b) reported similar observation on Vertisols of the Accra plain. The low production of dry matter on the Flat bed could be due to poor drainage of excess water during the wet periods. The raised beds on the other hand had furrows which served as drainage channels for excess water. The drainage channel might have resulted in good soil moisture condition for growth and development. Among the three raised beds, the Cambered bed performed better than both the Ridged and the Ethiopian beds. In most cases the Ethiopian bed did better or at least was equal to the Ridged bed. The better performance of the Cambered bed may be due to its higher water conservation and better drainage relative to the Ethiopian and the Ridged bed (Asiedu 1996). Improved soil moisture condition in the raised beds in addition to fertilizer application may have resulted in the significant treatment effect observed in the grain yield (Table 4.40). At all levels of fertilizer application, the raised beds produced higher dry matter yield than the Flat bed. This could be attributed to improved moisture conservation resulting in efficient utilisation of fertilizer.

At each level of fertilisation, the RAE was highest on the Cambered bed and least on the Flat bed (Table 5.1). The RAE of the Cambered bed at 50 % rate of fertilizer application was highest among all the Landforms. The low RAE obtained with the root could be attributed to the practical difficulty in efficient sampling of the maize roots from the Vertisols. At 50 % fertilizer application, maize on the Cambered bed was able to obtain adequate P for higher growth. On Cambered bed raising fertilizer rate from 50 % to 100 % did not result in corresponding increases in dry matter production (Tables 4.23; 4.32; 4.35; 4.38 and 4.40). This may be due to the fact that 50 % fertilizer rate supplying adequate nutrient for optimum maize growth. Also at both 50 % and 100 % level of fertilizer application, the Ridged and the Ethiopian beds always performed better than the Flat bed. These two raised beds were agronomically more efficient than the Flat bed (Table 5.1). The lower dry matter yields compared to that found on the Cambered bed could have resulted from relatively longer time taken for water to drain out of the surface of the Ridged and the Ethiopian bed compared to the Cambered bed which has broader furrows. The Flat bed on the other hand had drainage problems leading to poor root growth (Table 4.35). The Flat beds were flooded for a longer period after a heavy rainfall. This observation supports one of the advantages of raised beds stated by Kowal and Stockinger (1973). They observed that aeration is enhanced during wet periods as the furrows serve as open drains. The dry grain weight of the Ethiopian bed was significantly higher than that of the Ridged bed. This might be due to relatively better drainage and higher water conservation of the Ethiopian bed compared to the Ridged bed. Dua-Yentumi *et al.*(1992 b), observed that during wet periods it takes longer period for the Ridged bed to drain off its excess surface water compared to the Cambered bed. According to Asiedu (1996), conservation of water was better in the Cambered bed than the other raised beds.

This might have aided continuous root absorption and plant growth since moisture level in soil affects availability of soil P to crops (Finck and Venkateswarlu 1982).

Regression of dry weight on the nine soil variables suggests that the Landforms influenced dry matter yield greatly as it was selected as the single best predictor variable (Appendix 2). After the maize had tasselled and the root system well developed, the influence of Landform became reduced when compared to the early stages of maize growth. This implies that the moisture status of Landform was very significant to the dry matter production at the early stages when rainfall was relatively high, hence the high relationship between dry matter and the Landform. In fact, with dry matter yield of leaf, stubble and cob, the Landform was the single best predictor among the nine predictors variable(Appendix 2).

Influence of the fertilizer rate on dry matter yield before maize tasselled was quite high. It was always selected among the best subset of predictors of dry matter production (Table 4.26). On the contrary, the fertilizer rate was rarely selected among the best subset of predictor variables after maize had tasselled. Phosphorus requirement is critical at the early stages of the plant growth. Apart from cob and grain dry weight, rate of fertilizer applied as a variable was not selected among the best predictor variable of dry matter yield (Table 4.27). This supports the knowledge that the growth stage of the plant at which fertilizer application is done influenced P uptake and dry weight production.

Table 5.1. Relative Agronomic Efficiency of maize on four Landforms at three rates of fertilizer application.

Plant Part	Rate of fertilizer applied -- %--	F	R	EB	CB	F 1	CB 1[a]	F 2[a]	CB 2
		%							
Leaf	0	*	30.93	39.12	53.67	*		*	
	50		41.93	10.92	77.62		5.6		29.24
	100		50.88	50.11	58.24				
Stubble	0		27 .81	29.03	31.31				
	50		83.81	74.22	86.73		2.74		32.79
	100		48.89	38.01	53.73				
Root	0		12.12	8.43	49.61				
	50		7.51	1.47	9.34		13.38		3.90
	100		6.36	1.07	15.43				
Cob	0		12.10	15.79	31.86				
	50		10.58	25.81	63.12		13.96		11.85
	100		19.92	9.05	24.66				
Grain	0		4.55	43.84	42.77				
	50		4.42	13.71	75.50		19.15		17.28
	100		2.12	4.87	21.55				

- Flat bed is assigned RAE of 100 %. The other RAE's are percentages above the Flat
- bed.

a On-farms 1 and 2

5.3 Plant P concentration, rate of fertilizer applied and Landform

The plant's need for phosphorus is crucial during the early growth stages and uptake is higher if there is sufficient available P. According to Hagin and Tucker (1982), the P taken during this time may be sufficient for the whole growing period.

Phosphorus concentration in ear-leaf at tasselling stage was significantly influenced by fertilizer application (Table 4.22). Increasing the level of fertilisation resulted in significant decrease in the P concentration in the plant. With low levels of soil available P (averaging 3.03 ug/g) increasing the levels of fertilizer application led to increased availability of phosphate in the soil. This resulted in the plant obtaining sufficient level of P for increase dry matter production. This may have caused nutrient dilution as evidenced by reduced P concentration with increasing fertilizer application (Table 4.22). This finding supports that of Beckwith (1964) who reported that there was a minimum value of nutrient which is required by most plants to attain optimum growth. Noggle and Engelstad (1972) revealed that in cases of severe deficiency, nutrient concentration in the plant decreases with first application of nutrient to the soil. This, they explained is due to stimulated growth and subsequent dilution of particular nutrient element.

The non significant differences observed in P concentration as fertilizer level was raised to 100 % in all the Landforms could be due to the fact that greater absorption is compensated for by growth and increased biomass production resulting in a dilution effect. This explanation corroborates similar observation made by Noggle and Engelstad (1972). The low P concentration on the Cambered bed may imply efficient P utilisation by the plant on this landform. This is confirmed by the highest dry matter yield on the Cambered and the negative correlation obtained for the dry matter yield with the respective P-fractions from the raised beds. The reverse is true for the Flat where high P concentration gave low dry matter yield.

At harvest, P uptake in the stubble, cob and grain was significantly increased by higher levels of fertilizer added to the soil. Phosphorus uptake by the leaf strongly correlated with dry matter yield of maize at harvest (Table 5.2). This is because the leaf P uptake at the tasselling stage has been found to be very critical to dry matter yield at harvest. This observation supports that of Andre' (1984), who observed that P uptake by maize is reflected in the uptake by the ear-leaf at the tassselling stage. Addition of fertilizer to the raised beds resulted in higher uptake than that of the Flat bed. This could be due to better drainage and higher water conservation of the raised beds. The low P uptake on the Flat bed could be due to poor root aeration during the wet periods, leading to reduced growth which is reflected by lower dry weight (Table 4.22).

The higher uptake of P on the Cambered bed compared to the Ridged and the Ethiopian beds at all levels of fertilizer application could be due to higher water conservation by Cambered bed, making nutrient absorption possible even at relatively dry period. For this reason the Cambered bed even at 0 % rate of application had higher P uptake than other beds. This resulted in efficient utilisation of fertilizer on the Cambered bed as evidenced in higher organic matter production (Table 4.40). According to Le Mare (1987), response to phosphate is sometimes related to soil moisture levels.

Table 5.2. Correlation between leaf P uptake at tasselling and dry matter yield of the maize.

Dry weight of maize:	Leaf	Stubble	Root	Cob	Grain
Leaf P uptake	0.893*	0.865*	0.771*	0.724*	0.536*

* Significant at $P < 0.05$

5.4 Soil total P and dry matter yield

Soil total P at all the 3 stages of maize growth was not significantly influenced by either the fertilizer or landform treatment. This means that total P was more related to the origin of the Vertisols rather than treatment (Singh and Venkateswarlu 1985). Apart from soil organic P, which was essentially an external input, total P did not correlate with any of the other P-fractions (Tables 5.3 and 5.4). Though available P in the soil before the maize tasselled was quite high (Table 4.7) the correlation between it and total P was not significant. This means that total P contribution to soil available P was not statistically significant.

After the maize had tasselled, total P in the soil correlated even less with various P fractions. This means that the soil total P content may not be of much importance as far as P availability to maize in the Vertisol is concerned. The best subset regression analysis indicated that total P in the soil before and after the maize had tasselled was not selected among the best subset of predictors of dry matter weight of the maize (Tables4.26 and 4.27). It has been noted that although soil total P may be high, availability of P to crops may still be a problem (Dudal, 1965; Hubble, 1984). The soil total P is therefore, not a good indicator of soil available P content in the Vertisol.

Table 5.3. Correlation between predictor variables before maize tasselled.

	Rate of P	Total P	Availa-ble P	Organic P	Fe-P	Al-P	Ca-P	Occluded P
1. Rate of P	1.000							
2. Total P	-0.136	1.000						
3. Available P	0.056	-0.328*	1.000					
4. Organic P	-0.634*	0.382*	-0.145	1.000				
5. Fe-P	-0.734*	0.120	-0.055	0.435*	1.000			
6. Al-P	-0.116	-0.124	0.149	0.174	0.151	1.000		
7. Ca-P	-0.207	0.218	-0.171	0.236	0.234	0.165	1.000	
8. Occluded P	-0.707*	-0.029	0.004	0.495*	0.555*	-0.065	-0.119	1.000

* Significant at $P < 0.05$

Table 5.4. Correlation between predictor variables after maize tasselled.

	Rate of P	Total P	Available P	Organic P	Fe-P	Al- P	Ca-P	Occluded P
1. Rate of P	1.000							
2. Total P	-0.061	1.000						
3. Available P	0.214	0.149	1.000					
4. Organic P	-0.194	0.418*	0.240	1.000				
5. Fe-P	0.274	0.086	0.427*	-0.175	1.000			
6. Al-P	0.004	-0.016	0.105	-0.025	0.240	1.000		
7. Ca-P	0.108	0.205	0.319*	0.415*	0.230	0.045	1.000	
8. Occluded P	-0.191	0.086	-0.151	0.329*	-0.443*	-0.082	0.180	1.000

- Significant at $P < 0.05$

5.5 Soil organic P and dry matter yield

Soil organic P during the 3 stages of maize growth constituted between 24 - 27 % of the soil total P. Acquaye and Owusu Bennoah (1989) reported that soil organic matter in the Vertisols of Ghana ranged between 49 and 69µg/g and this constituted 21 to 40 % of the total P. Like the total P, the amount of organic P in soil was not significantly influenced by the Landforms and the rate of fertilizer application. The amount of the organic P content in the soil before maize tasselled was higher than the tasselling and maturity stages of the maize growth. This may be due to decomposition of organic matter which had accumulated during the fallow period. Black and Goring (1953) reported a positive relationship between organic matter and organic P in soils. There was a high correlation between organic P and inorganic P fractions (Tables 5.3 and 5.4). This high correlation suggests mineralisation of organic P to inorganic P during the period. This corroborates the report by Tisdale and Nelson (1966) that organic P is readily mineralised into inorganic P under tropical conditions.

Regression of dry weight on the predictor variables viz:, rate of P, total P, available P, organic P, aluminium P, calcium P, iron P and occluded P before the maize tasselled indicated that organic P was among the best subset of predictors that contributed to dry matter production (Table 4.26). The relationship between organic P and the dry weight of leaf, stubble, root, cob and grain was significant (Table 4.24). This indicates that organic P influenced maize growth and yield.

Soil organic P did not change much during the last two stages of maize growth (Tables 4.5 and 4.6). Generally, there was less soil organic P content at the tasselling stage compared to soil organic P at the harvest. This could be due to higher decomposition of organic matter in the soil compared to rate of addition of litter.

5.6 Soil available P and dry matter yield

Soil available P before maize tasselled was the highest among the three stages of maize growth. It reduced progressively from 7.63 to 4.69 μg/g after the maize tasselled and finally to 3.95 μg/g at harvest. The reduction in P during these growth stages could be attributed to uptake by plant, P-sorption and erosion losses.

P uptake in leaf at tasselling constituted about 31.77 % of the total maize output (Table 5.5). The reduction in available P in soil at tasselling could be attributed primarily to P uptake. Uptake was always higher on the raised beds compared to the Flat bed, though equal levels of fertilizer were applied to all the Landforms (Tables 4.30, 4.33 and 4.36).

Table 5.5. Percentage proportions of various parts of maize to the total maize output.

Part of maize	P concentration	Dry matter	P uptake
	%		
Leaf	37.96	21.10	31.77
Stubble	16.58	23.08	13.62
Root	7.49	9.18	2.84
Cob	9.79	8.94	3.45
Grain	28.17	37.70	48.45

The relatively low soil available P in the Flat bed inspite of low P uptake (Tables 4.30, 4.33, 4.36, 4.39, 4.42) may be due to erosion. Lack of adequate drainage on the Flat bed resulted in the soil being flooded or eroded during wet periods. This might have resulted in loss of P and other nutrients. According to Owusu-Bennoah and Dua-Yentumi (1989), one major problem of Vertisols of the Accra plains is flooding due to its slope (0.1 1.0 %). Flooding during wet periods lead to poor root aeration which results in poor root development, low plant nutrient uptake and poor growth (Tables 4.35).

Among the raised beds, P uptake and the dry matter yield was significantly higher on the Cambered bed than on the Ridged or the Ethiopian bed at the same level of fertilizer application (Tables 4.23 and 4.30). The rate of applied fertilizer and Landforms did not significantly influence soil available P at harvest (Table 4.9). There was, however, relatively low available P levels in the Cambered bed compared to the Flat bed. This may be attributed partly to higher P uptake on the Cambered bed (Tables 4.30, 4.33 and 4.36) which facilitated better root development and efficient root exploitation. There was a significant positive correlation between soil available P, and dry weight of maize leaf at tasselling stage of the maize (Table4.25) compared to a non significant correlation between soil available P and dry weight before the maize tasselled (Table 2.24). This means that at early stages of the maize growth especially at tasselling, the plant was more responsive to soil available P.

Phosphorus uptake of the maize ear leaf at tasselling correlated significantly with both soil available P and grain yield. This implies that the ear leaf P uptake could be used as yield index to correct P deficiencies in maize (Table 5.4). This view is supported by Andre' (1984) who argued that P uptake by maize ear leaf at tasselling stage reflects the nutritional status of the crop and serves as an indicator to dry weight yield. Regression analysis indicated that available P was among the best subset of predictor variables of dry weight production (Tables 4.28 and 4.29).

Soil available P at harvest ranged between 2.87 and 3.95 μg/g. This was generally lower than the available P at the two earlier growth stages. The residual P may be available to the succeeding crop and may not be absolute because of the difficulty in its determination. Since P uptake was significantly higher in the raised beds compared to the Flat bed, the relatively low level of soil available P on the Flat bed may be attributed to erosion. The lower levels of soil available P in the Cambered bed at harvest compared to those of the Ridged or the Ethiopian beds can be attributed to higher P uptake which resulted in higher dry matter yield in the Cambered bed (Table 4.35). Soil available P significantly correlated with Ca-P and Fe-P fractions after the maize had tasselled (Tables 5.3 and 5.4). Since there was no significant relationship between Ca-P and Fe-P, it means there was independent contribution from each fraction to the available P which was manifested after the tasselling stage. The varying rainfall pattern during the maize growing period might account for the independent and varying contribution of the Ca-P and Fe-P to the labile-P pool.

5.7 Active inorganic P fractions and dry matter yield

Initial soil analysis indicated calcium as the dominant cation in the soil. This might have resulted in larger proportion of the applied fertilizer being tied up to form high levels of Ca-P in all the landforms. About 75 % of the inorganic active P was Ca-P while Al-P and Fe-P formed about 16 and 2 %, respectively. Acquaye and Owusu-Bennoah (1989) reported that inorganic active P was tied up with calcium rather than aluminium or iron. Data obtained by ICRISAT (1984), about two-thirds of the phosphate of some Indian Vertisols were associated with calcium, one-third with iron and very little with aluminium.

There was significant negative correlation between Fe-P and dry matter yield (Table 4.24). At tasselling, however, there was significant positive correlation with both Ca-P and Fe-P (Table 4.25). The significant positive correlation between Ca-P and dry matter yield could be due to greater amount of Ca-P in the labile P resulting in higher Ca-P uptake. Also relatively poor drainage conditions in the Vertisols might have resulted in the release Fe-P before and after tasselling when rainfall was high compared to after harvest. This explains the high correlation between Fe-P and dry matter production. and confirms the observation by Russell (1973) that this form of P more than other fractions, is the source of available P under poorly drained conditions.

The drop in Fe-P relative to the stage of growth (Tables 4.16 and 4.18) may be associated with the rainfall pattern. The maize crop matures towards the end of the rainy season. The higher the soil moisture content, the greater the reducing conditions and the higher the Fe-P production in the soil. As rainfall reduces, there is a corresponding increase in the redox-potential with corresponding increase in the oxidation state, hence lower Fe-P production in the soil at harvest (Table 4.18). This observation is supported by a marked decrease in Fe-P associated with raised beds where aeration is better than the Flat bed (Tables 4.17 and 4.18).

Regression analysis indicated that Fe-P was one single predictor variable that strongly influenced dry weight of leaf at the tasselling stage (Appendix 2). This may be due to the high soil moisture condition as a result of high amount of rainfall (Table 3.1). Under reducing conditions, especially on the Flat bed, Fe-P may have contributed substantially to the labile P.

Le Mare (1987) and Russell, (1973) agreed that under poorly drained conditions of Vertisols, Fe-P will contribute more to available P than other P fractions. The influence of Fe-P on maize yield could therefore be due to the imperfect drainage of the Flat and the Ridged beds during the wet periods.

CHAPTER SIX

6 SUMMARY AND CONCLUSION

During the minor season of August 1994, four landform (Flat, Ridged, Ethiopian and Cambered bed) technologies on the Vertisols of the Accra plains were investigated to find which will be most efficient in terms of dry matter production of maize. Three levels of compound fertilizer, (0, 50 and 100 % of the recommended rate of 15-15-15) were applied. Agronomic efficiencies of these Landforms were determined using P uptake and dry matter production of maize. Inorganic P fractions (Ca-P Al-P and Fe-P) and their relationships with dry weight of leaf, stubble, root, cob and grain were studied during the period in all the Landforms. Phosphorus uptake on the four Landform technologies at the different rate of fertilizer application by the leaf at tasselling and by the stubble, root, cob and grain at harvest were determined.

The field trial was sited in three localities of the Accra plains : Agricultural Research Station (ARS, Kpong) - as on-station site and two on-farm sites at Buedo farm and New Frontier farm.

The research findings indicated that the raised beds, namely the Ridged, the Ethiopian and Cambered bed, significantly outperformed the Flat bed in P uptake and dry matter production. Among the raised beds, the Cambered bed gave the highest dry matter production. Generally, the Ethiopian bed did better than the Ridged bed, though with some plant parts, viz. for stubble and root the reverse was the case. Dry matter production and P uptake followed a decreasing trend of

CB >EB = R > F at $P<0.05$.

Maize production on the Vertisols of the Accra Plains is improved if excess water is drained to prevent water logging conditions during the wet periods, while conserving enough water in the soil for crops use. As a result of the low levels of soil available P in these soils, dry matter production responded readily to fertilizer P application.

It was observed that during the wet periods, drainage was better on the raised beds than on the Flat bed. It took a longer period for water to drain off the Flat bed after heavy rainfall.

Addition of fertilizer resulted in significant increases in dry matter production. Phosphorus uptake and dry matter production was significantly influenced by Landform and application of fertilizer. Dry matter yield on the Cambered bed, unlike the other Landforms, did not increase significantly when the fertilizer level was raised from 50 to 100 %. Relative Agronomic Efficiency of the raised beds at all levels of fertilizer application was higher than that of the Flat bed. The Cambered bed was more efficient agronomically, than the Ethiopian and the Ridged beds. Efficient utilisation of P occurred on the Cambered bed and was most significant at the 50 % fertilizer rate as evidenced by the highest grain yield of 2.29 tons/ha. This strongly suggests development of the appropriate Landform could reduce the quantity of fertilizer input.

Phosphorus uptake was highest in the maize grain, 48.3 %, followed by the leaf, 32 %, stubble, 13.6 % cob, 3.45 % and root, 2.84 %. The grain formed about 38 % of the total dry matter produced by the maize plant.

Soil available P was low in all the Landforms. Addition of fertilizer resulted in increased soil available P levels in all the landforms. Though total soil P was quite high, its contribution to soil available P was negligible. Soil organic P content was about 25 % of the total P. The significant correlation between available P and soil organic P suggested the importance of mineralisation in contributing to the needs of the maize crop.

Generally, in all the Landforms, negative available P balance was observed at the end of the planting season. Even initial higher rate of fertilizer application did not significantly raise the residual P in the soil. The Ca-P was the dominant inorganic P and it contributed 78 % of the total inorganic phosphates. Most of the P in the fertilizer applied was tied up with calcium rather than with iron or with aluminium. The Ca-P strongly correlated with P uptake and dry matter production. While Ca-P and Al-P did not change much during the period of maize growth, Fe-P was reduced to about half its original value.

Regression analysis indicated that before the maize tasselled, Landform, organic P, rate of fertilizer application and available P accounted for 68 % of the variations in dry matter production. After tasselling these four factors accounted for 60 % of the variations.

The influence of Landform on dry matter production was quite significant particularly on the Cambered bed where with better drainage and higher water conservation than the rest of the raised beds, high dry matter yield of maize was obtained at half the recommended fertilizer dose on the Vertisols of the Accra plains.

Suggested future work

1. The economic implications of the fertilizer x landform interaction should be investigated.
2. The trial should be repeated over two growing seasons and should include some vegetables common in the area.
3. On-farm trials should be extended to more areas.
4. The role of Ca-P and Fe-P in the Vertisols at different stages of the crop growth stage needs further investigation.

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APPENDIX

Appendix 1

Analysis of Variances (On-Station)

Sources	df
Replications	3(4-1)
Landforms	3(4-1)
Error	9(4-1)(4-1)
Rate of fertilizer	2(3-1)
Interaction	6(4-1)(3-1)
Error	24
Total	47

Analysis of Variance (On-Farm)

Sources	df
Replication	2 (3-1)
Landform	1 (2-1)
Error	2
Total	5

Appendix 2

Best Subset Regression of dry matter weight of maize leaf at tasselling on nine predictor variables.

SUBC> NVars 1 9;
SUBC> Best 2.

Vars	R-sq	Adj. R-sq	C-p	s	RaLf	Avaite	OrtP	FelP	AlgP	OcCa-P	cl-P	-P	-P
1	14.3	12.8	63.5	6.9947	X								
1	13.7	12.2	64.3	7.0199						X			
2	48.5	46.6	17.8	5.4715		X			X				
2	37.6	35.4	33.0	6.0206	X					X			
3	56.5	54.2	8.7	5.0722	X	X			X				
3	56.2	53.8	9.1	5.0890		X		X	X				
4	60.5	57.6	5.1	4.8788	X	X		X	X				
4	58.3	55.3	8.1	5.0073	X	X			X	X			
5	61.4	57.8	5.8	4.8664	X	X		X	X	X			
5	61.3	57.7	6.0	4.8722	X	X		X	X			X	
6	62.5	58.2	6.3	4.8409	X	X	X	X	X			X	
6	62.3	58.0	6.6	4.8537	X	X		X	X	X		X	
7	63.0	58.0	7.5	4.8525	X	X	X	X	X	X		X	
7	63.0	58.0	7.6	4.8528	X	X	X	X	X		X	X	
8	63.8	58.2	8.4	4.8452	X	X	X	X	X	X	X	X	
8	63.2	57.5	9.2	4.8852	X	X	X	X	X		X	X	X
9	64.1	57.7	10.0	4.8737	X	X	X	X	X	X	X	X	X

Appendix 3

Best Subset Regression of dry matter weight of maize grain at tasselling on nine predictor variables.

SUBC> NVars 1 9;
SUBC> Best 2.

Best Subsets Regression of Dmm

```
                                  A     O
                                  v     c
                                R aOFACc
                                a irelal
            Adj.                Lttlg----
Vars  R-sq  R-sq   C-p       s  fePPPPPPP

   1  10.9   9.3  34.4  76.393     X
   1   9.0   7.4  36.3  77.185    X
   2  26.3  23.7  20.8  70.078   X   X
   2  23.7  21.0  23.4  71.290      X   X
   3  37.3  33.9  11.6  65.215   X   X   X
   3  36.8  33.4  12.1  65.451   X X  X
   4  43.1  39.0   7.7  62.661   X X  X   X
   4  42.6  38.4   8.2  62.942   X   X X  X
   5  47.1  42.2   5.6  60.973   X  X X X  X
   5  46.5  41.5   6.3  61.351   X X  X X  X
   6  49.9  44.2   4.8  59.904   X X X X X  X
   6  48.3  42.5   6.4  60.854   X  X X X  X X
   7  50.6  44.0   6.1  60.056   X X X X X  X X
   7  49.9  43.2   6.8  60.474   X X X X X X X
   8  50.7  42.9   8.0  60.612   X X X X X X X X
   8  50.6  42.9   8.1  60.626  X X X X X X  X X
   9  50.7  41.8  10.0  61.187  X X X X X X X X X
```

Appendix 4

ABBREVIATIONS

Lf	Landform
Rate	Rate of P applied
tP	Soil total phosphorus
Avail.P	Soil available phosphorus
Org-P	Soil organic phosphorus
Fe-P	Iron phosphate
Al-P	Aluminum phosphate
Ca-P	Calcium phosphate
Occl-P	Occluded phosphate