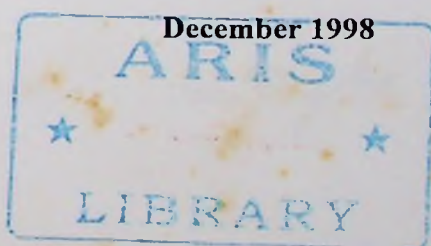


**PHOSPHORUS STATUS AND SORPTION CHARACTERISTICS IN
SOME VERTISOLS OF UGANDA.**

NELSON OLANI. B.Sc (Agric.) HONS.

**Thesis submitted in partial fulfilment of the requirements for Master of Science
in Agriculture (Soil Science) degree, Makerere University.**



Declaration.

I, Nelson Olani, declare that this is my original work and has never been submitted for a higher degree in another University.

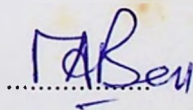
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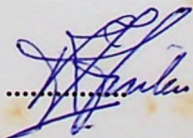
This thesis has been submitted with our approval as University supervisors.



MATEETE. A. BEKUNDA (PhD).

Date.....

16/12/98



JACOB ANIKU (PhD).

Date.....

18/12/98

Dedication.

To my wife Nancy

Acknowledgement.

This study was made possible through a scholarship offered to me by the National Agricultural Research Organisation (NARO) under the Agricultural Research and Training Project (ARTP), and I am highly indebted to Dr. J. P. Esele, Director Serere Agricultural and Animal Research Institute (SAARI), for nominating me for the scholarship.

I extend my gratitude to Dr. M. A. Bekunda and Dr. J. Aniku for accepting to supervise the research work and for their commitment to the work. Their constructive criticisms during the course of the research and writing up this thesis is highly appreciated. I thank all the staff of the Department of Soil Science, Makerere University, for all the assistance they offered to me during the course of my study. The entire administration of SAARI is acknowledged for the assistance offered to me during collection, drying and transportation of the soils to Makerere University.

Finally, I extend my thanks to all my fellow students who directly or indirectly assisted me during data collection and analysis.

Summary

Studies were conducted to determine the phosphorus status and sorption characteristics of three Vertisols of Uganda collected from Kamutur in Kumi District, Olweny Swamp Rice Irrigation Project in Lira District and Sironko in Mbale District. Soil site and profile descriptions were done to confirm that the soils in the selected areas are Vertisols. The phosphorus status and sorption characteristics of the soils were determined by sequentially partitioning their different inorganic phosphorus fractions and establishing their ability to sorb phosphorus. The effects of organic matter application on the phosphorus sorption parameters, and on the availability of native phosphorus were determined. Changes in the inorganic phosphorus fractions after incubation with superphosphate were also determined.

There were quantitative differences in the status of native inorganic phosphorus in the soils. Bray I phosphorus in the composite samples of the surface soils (0-20 cm) was high (39.5 ppm P), medium (11.6 ppm P) and low (6.6) in soils from Sironko, Kamutur and Olweny, respectively. Total phosphorus was highest in Kamutur soil (1322 ppm P), followed by Sironko soil (374 ppm P) and lowest in Olweny soil (335 ppm P). Of the active inorganic phosphorus fractions (aluminum-bonded phosphorus, calcium-bonded phosphorus and iron-bonded phosphorus), aluminum-bonded phosphorus (Al-P) was the predominant fraction in all the soils; forming 62.2%, 89.7% and 65.8% of the total active inorganic phosphorus fractions in

Kamutur, Olweny and Sironko soils respectively. Application of 30 mg P kg^{-1} soil as single superphosphate in Kamutur and Olweny soils significantly increased all the active inorganic phosphorus fractions; the increase in Al-P being significant only at 90 days of incubation.

The soils differed in their ability to sorb added inorganic phosphorus and the standard phosphorus requirements (SPR) were of the order: Kamutur soil (46.61 ppm P) > Olweny soil (36.08 ppm P) > Sironko soil (8.62 ppm P). Phosphorus sorption in the soils from Kamutur and Olweny deviated from the conventional Langmuir equation and conformed to the binary (two-surface) Langmuir relationship. This is an indication of the existence of two types of sorption sites in the soils having different affinity for phosphorus; and this results from creation of new sites due to displacement of structural silicates of clays at high concentrations of phosphorus in equilibrium solution. For the Sironko soil, phosphorus sorption conformed to conventional Langmuir equation suggesting sorbed phosphate formed a monolayer on the sorbent surfaces. Application of organic matter, in form of cellulose and starch, at 20 g kg^{-1} soil increased phosphorus sorption maxima in the soils from Kamutur and Olweny but decreased that for the soil from Sironko. The increases in Kamutur soil were 5.5, 6.5 and 12.4 ppm P at 30, 60 and 90 days of incubation respectively. For Olweny soil the increases were 39.9, 42.4 and 47.8 ppm P at 30, 60 and 90 days of incubation respectively. In Sironko soil the decrease (of 4 ppm P) in phosphorus sorption was significant only at 60 days of incubation.

No immediate phosphate fertilization is recommended for Sironko soil because of the high level of available phosphorus, but for Kamutur and Olweny soil there is need for phosphate fertilization for higher crop yields. The standard phosphorus requirements indicate that Kamutur soil requires $93.22 \text{ kg P ha}^{-1}$ and Olweny soil $72.16 \text{ kg P ha}^{-1}$ for optimum crop growth. However the actual economic rates should be confirmed from field experiments.

Incubation studies showed that most of the inorganic phosphorus added in Kamutur and Olweny soils was recovered as calcium-bonded phosphorus followed by aluminum-bonded phosphorus at 30 and 60 days of incubation. This implies that most of the applied phosphorus would be available to crops in the short term.

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CHAPTER ONE

INTRODUCTION

The phosphorus status of a soil is one of the most important factors that control the response of a crop to phosphate fertilizers. Traditionally the phosphorus status of a soil has been assessed by one of several soil test methods which estimates the quantity of plant available phosphorus using extracting solutions such as dilute concentrations of strong acids (Nelson et al, 1953); dilute concentrations of strong acids plus a complexing ion (Bray and Kurtz, 1945); dilute concentrations of weak acids (Ballard and Pritchett, 1975); and buffered alkali solutions (Olsen et al, 1954; Colwell, 1963). In view of the current emphasis on environmental quality, soil tests are a logical tool to determine whether phosphate fertilizers should or should not be applied to a soil.

Studies on the forms and distribution of various forms of phosphorus provide useful information in assessing the available phosphorus status of soils (Uzu et al, 1975), evaluating reaction products of phosphorus fertilizers in soils (Olsen and Flowerday, 1971) and determining relative weathering of soils (Lekwa and Whiteside, 1986). The phosphorus that is removed by a chemical extractant is affected by the amount and nature of phosphorus present, and by the capacity of the soil to sorb phosphorus (Halm and Ahenkorah, 1978). Phosphorus sorption also plays an important role in determining the ultimate availability of phosphatic fertilizers to plants and the agronomic effectiveness of the fertilizers.

The feasibility of correcting phosphorus deficiencies by fertilizer application might be decided by the sorption characteristics of the soil, and estimates of the retention capacities of the soils are useful and indicative of the amount of phosphate fertilizer that should be required for high production (McKenzie et al, 1977). Therefore, information on the inorganic phosphorus fractions and sorption capacities are primary requirements for the development of appropriate guidelines for management of phosphorus in soils.

1.1 Importance of Phosphorus

Phosphorus is an important nutrient element as it plays both direct and indirect roles in the metabolism of plants and animals. It is a component of adenosine diphosphate (ADP) and adenosine triphosphate (ATP) which are involved in energy transformations in plants and animals. It is also a component of deoxyribonucleic acid (DNA), the seat of genetic inheritance in plants and animals (Brady, 1984). Kolar and Grewal (1989) found that abundant available phosphorus in the root zone helped both rice and wheat crops to attain higher leaf area index and chlorophyll contents in the leaves. This enabled the crops to trap more photosynthetically active radiation which increased the number of ear bearing shoots, grains per panicle, grain weight and grain yield. Phosphorus also influences the utilization of other plant nutrients by crops. In the Sudan Gezira, Ayoub (1986) found that application of phosphorus to irrigated wheat significantly increased the uptake of soil-and fertilizer-nitrogen, resulting in

higher yields of both straw and grains. A high dose of nitrogen without phosphorus application reduced yield of sorghum (Farah and El Feki, 1990).

The other beneficial effects of phosphorus on crops are that:

- (i) it speeds up maturation (Hanway and Olson, 1980; Kubota et al, 1993);
- (ii) it stimulates good root development, particularly lateral and fibrous roots (Brady, 1984; Hajabbasi and Schumacher, 1994);
- (iii) it strengthens straws in cereals, helping to prevent lodging (Brady, 1984);
- (iv) it improves nutritional qualities of crops, especially forages, vegetables and fruits (Gardner and Roth, 1983).

Phosphorus influences biological nitrogen fixation. The enzyme nitrogenase involved in nitrogen fixation requires ATP which has phosphorus as a component. Phosphorus application increased nitrogenase activity in lucerne (Crews, 1993), nodule number and dry weight, and the yield of seeds and straw in Faba beans, chickpea and lentils (Abdel-Wahab et al, 1994), and amount of nitrogen fixed and the yield of soybeans (Baz et al, 1985; Luyindula et al, 1994).

Phosphorus affects growth and reproduction in animals. It is one of the major structural elements of skeletal tissues, uniting calcium and carbonate to form compounds that give rigidity to bones and teeth (Hays and Swenson, 1984). In dairy animals phosphorus deficiency has been shown to cause decline in milk

production and depraved appetite (Salisbury et al, 1978; Reid, 1980). Phosphorus deficiency also causes reproductive disturbances. Carstairs et al (1975) observed that Holstein heifers fed high-energy, low-phosphorus diets had a longer interval to oestrus after calving than animals maintained on high-energy, high-phosphorus rations. Sheep ate more of feed grown with phosphorus and digested it better with resultant increased production (Ozanne and Purser, 1980).

Phosphorus has been noted to be one of the most limiting nutrients to crop production in many soils of Uganda (Zake, 1993), including Vertisols common in the rice growing areas of Uganda

1.2 Vertisols

Vertisols are deep, dark coloured clayey mineral soils characterized by deep, wide cracks during the dry season, gilgai micro relief, intersecting slickensides and/or wedge-shaped structural aggregates in the subsoil (Seghal and Bhattacharjee, 1987). These characteristics are mainly due to high clay content ($> 30\%$) of swelling type clays. The most common nutrient deficiency in Vertisols is that of nitrogen, followed by phosphorus (Bansal and Sekhon, 1994; Dudal, 1965; Le Mare, 1987); and for phosphorus deficiency is common in Vertisols derived from granite parent material (Katyal et al, 1987).

In Uganda the soils that have been classified as Vertisols occur mainly in the Eastern and North-eastern parts of the country (Appendix 1). This classification was based on the results of the reconnaissance soil surveys carried between 1958-1960. It is not possible to ascertain whether all these soils match the definition of Vertisols but from the available characterisation information (Harrop, 1960; Ollier, 1959; Ollier and Harrop, 1959 and Wilson, 1959) the majority of the soils fit the Vertisol description. There is no accurate estimate of the land surface occupied by Vertisols in Uganda because there has been no detailed systematic soil surveys covering the whole country. Harrop (1970), basing on the results of the reconnaissance survey, estimated the soils to cover approximately 3323 km² (332,300 ha); about 1.8 % of the land surface of Uganda. Therefore Vertisols form a potentially large area of agricultural production in the country. Some of these areas are currently under-utilised for crop production, partly because of the poor physical properties of the soils. But with increasing land limitations they are likely to be put to use and then soil nutrient deficiencies are likely to become a problem. Therefore, there is need to determine the nutrient status of soils so that remedial action is taken to correct any nutrient deficiency.

1.3 Problem statement and objectives

There has been very little investigation on the amount, nature and behaviour of phosphorus in Vertisols of Uganda. The native inorganic phosphorus fractions in the Vertisols have never been characterised and how these fractions are

affected by phosphorus fertilizer application is not known. The phosphorus sorption characteristics of the Vertisols have not been determined and the phosphorus sorption parameters have not been quantified. In acid oxidic soils there is evidence that organic matter application either decreases, increases or does not affect phosphorus sorption (Sample et al, 1980) but literature on similar studies in Vertisols is scanty.

The objectives of this study therefore were to determine:

- (i) the status of native phosphorus fractions of some Vertisols of Uganda and how these fractions are affected by application of phosphorus fertilizers.
- (ii) the phosphorus sorption characteristics of the Vertisols and quantify the phosphorus sorption parameters.
- (iii) the effects of organic matter application on the phosphorus sorption characteristics and availability of native phosphorus in the Vertisols.

CHAPTER TWO

LITERATURE REVIEW

2.1 Vertisols

Vertisols are a group of soils with specific morphology, chemical and physical characteristics. Despite their unique attributes, Vertisols were not recognised as a separate class of soils until the 7th Approximation Soil Taxonomy was published in 1960 (Soil Survey Staff, 1960). The soils were formerly known by various names such as black cotton soils, black tropical soils, black earths, regur, cracking clays and grumusols. The name Vertisols was coined in the 7th Approximation Soil Taxonomy to group these soils in one Order. Differences within Vertisols are caused by differences in climate, slope and landform, the amount and composition of smectite clay minerals, and the nature of the saturating cations (Sehgal and Bhattacharjee, 1987).

In Soil Taxonomy (Soil Survey Staff, 1975) the definition of Vertisols is based on the following properties:

- (i) do not have a lithic or paralithic contact, petrocalcic horizon or duripan within 50 cm of the surface,

(ii) have 30 % or more clay in all subhorizons to a depth of 50 cm or more after the soil has been mixed,

(iii) have, at some time in most years, unless irrigated or cultivated, open cracks to a depth of 50 cm that are at least 1 cm wide and extend upwards to the surface or to the base of a plough layer or surface crust,

(iv) have one or more of the following;

- gilgai
- at some depth between 25 cm and 1 m, slickensides close enough to intersect,
- at some depth between 25 cm and 1 m, wedge-shaped natural structural aggregates that have their long axis tilted 10-60° from the horizontal.

In the FAO classification system (FAO, 1988) Vertisols are defined as soils having 30% or more clay in all horizons to a depth of at least 50 cm; developing cracks from the soil surface downwards which at some period in most years (unless the soil is irrigated) are at least 1 cm wide to a depth of 50 cm; having intersecting slickensides or wedge-shaped or parallelepiped structural aggregates to some depth between 25 and 100 cm from the surface with or without gilgai.

Vertisols are found mostly in sub-humid and semi-arid climates with moderate to high temperatures. They develop mainly on gentle slopes and most Vertisols

occur at low elevations and in flat gently undulating areas including plateaus and alluvial plains (Eswaran and Cook, 1988). However, some Vertisols such as Ethiopian Vertisols occur at higher altitudes and steep slopes (Swindale, 1988). Landform is an important factor contributing to the formation of Vertisols and this led to introduction of the terms "lithomorphic" and "topomorphic" Vertisols which have been used mainly in the French C.P.S.C (Commission of Pedology and Soil Cartography) classification system. The former term refers to the dominating influence of the parent rock and the latter term indicates that the variable topography is the major soil forming factor (Siderius, 1987).

In Soil Taxonomy (Soil Survey Staff, 1975) the Vertisols are divided into four sub-orders: Torrerts, Uderts, Usterts and Xererts. Torrerts are Vertisols of arid climates. Torrerts, unless irrigated, have in most years cracks that either remain open throughout the year or are closed for less than 60 consecutive days at a period when the soil temperature at a depth of 50 cm is continuously higher than 8°C. Uderts are the Vertisols of humid climates. They have cracks that open and close more or less irregularly over time according to the weather. Usterts are Vertisols of monsoon climates, of tropical and sub-tropical areas that have two rainy seasons and two dry seasons, and of temperate regions that have low summer rainfall. Xererts are Vertisols mostly found in areas with Mediterranean climates, with cool wet winters and warm dry summers. The first three sub-orders

are the ones common in Africa (Kanwar and Virmani, 1987). The sub-orders are further divided into great groups, essentially on the basis of the colour (Munsell chroma of the moist soil) of the surface horizon. The "chromic" great groups have a chroma of 1.5 or more dominant in the soil matrix throughout the upper 30 cm and the "pellic" great groups have a chroma of less than 1.5 (Eswaran and Cook, 1988). The pellic chromas reflect less-favourable drainage conditions, while the chromic great groups are better drained Vertisols. However, application of these criteria in soil surveys have shown that these colour differences are not generally correlated with drainage conditions (Dudal, 1989; Sehgal and Bhattacharjee, 1987).

In the FAO classification system of 1974 (FAO / UNESCO, 1974) Vertisols are divided into pellic and chromic Vertisols based on the chroma of the soil. However, in the FAO classification system of 1988 (FAO, 1988) the sub-division of Vertisols is based on base saturation and presence / absence of calcic or gypsic horizon. The sub-divisions are : eutric Vertisols, dystic Vertisols, calcic Vertisols and gypsic Vertisols. Eutric Vertisols have a base saturation of 50% or more at least between 20 and 50 cm from the surface, lacking a calcic or gypsic horizon. Dystic Vertisols have a base saturation of less than 50% at least between 20 and 50 cm from the surface, lacking a calcic or gypsic horizon. Calcic Vertisols have a calcic horizon or concretions of soft powdery lime within

125 cm of the surface, lacking a gypsic horizon. Gypsic Vertisols have a gypsic horizon within 125 cm of the surface.

In Uganda the soil series that have been classified and mapped as Vertisols are Bugusege, Kidepo, Ora, Sebei, Siroko and Weiga series (Anonymous, 1967) and they occupy an estimated area of 3323 km² (Harrop, 1970). This classification was based on the results of the reconnaissance soil surveys carried out in the country from 1958 to 1960 when these soil series were described in details (Harrop, 1960; Ollier, 1959; Ollier and Harrop, 1959; and Wilson, 1959). The Kidepo, Ora, Sebei, Siroko and Weiga series were classified as topomorphic Vertisols and Bugusege series as lithomorphic Vertisols (Anonymous, 1967). When correlated with the FAO/UNESCO system of soil classification (FAO/UNESCO, 1974) the Kidepo, Ora, Sebei, Siroko and Weiga soil series qualify to be classified as pellic Vertisols and the Bugusege soil series as chromic Vertisols.

2.1.1 Physical Properties of Vertisols

The diagnostic features of a Vertisol are cracks to a depth of 50 cm, at which depth the cracks should be at least 1 cm wide, and a high content (>30%) of swelling-type clays to a depth of 1 m. When rains come, water runs into the

cracks and the soil remoistens both from below and above. As the soil becomes moist the clays swell and the cracks close, generating pressure. The pressure is exerted in all directions, but the soil can move only upward and horizontally, resulting in soil movement in an intermediate direction at an angle from the horizontal. This is the probable origin of the slickensides, the gilgai and the wedge structure that are used in part to define the Vertisol soil order (Soil Survey Staff, 1975).

The physical properties and water relations of Vertisols are influenced by their swelling and shrinking properties. The soil consistency is sticky when wet and hard when dry. The cracks affect water intake in the soils at the beginning of the rainy season. A large proportion of rain water enters the soil when the initial rainfall is heavy but if the initial rainfall is slight the soil may be sufficiently moistened to close the cracks and later rainfall infiltrate only slowly and much of it may be lost as runoff. According to Burnett (1989) infiltration rates of Vertisols vary from almost infinity to extremely low, due in part to the high coefficient of expansion and contraction. While the cracks are still open water intake is very high but upon wetting the soils begin to expand, cracks close and infiltration rate declines. The saturated hydraulic conductivities of the soils are low and this results in poor aeration of the soils which may retard root development.

The soil structure of Vertisols largely depends on how the soils react to wetting and drying. The structure is often well developed and easy to see in the dry state when the surface horizons are characterised by huge strongly developed prismatic primary structures which break into angular to sub-angular secondary aggregates. Dry season desiccation of Vertisols often results in formation of a loose and dusty surface, a phenomenon referred to as "self-mulching" (Burford, 1987). The degree of aggregation and its stability in the wet state is low. In the wet season both the primary and secondary structures are almost completely destroyed, reducing the surface horizon to a massive block (Woldeab, 1988). The aggregates are therefore regarded as merely the products of shrinkage with little or no aggregate stability when the soils are wetted.

The total water holding capacity of Vertisols is high both at field capacity and at wilting point. The implication of this is that if the moisture content of the soil is below wilting point a large amount of water is needed to bring the moisture content to a range within which some of the water becomes available to the plants. The bulk densities of Vertisols vary greatly and this is caused by swelling and shrinking which accompany changes in the moisture content of the soils. The soils have high bulk densities when dry and low bulk densities when wet (Woldeab, 1988).

There has been no systematic study of the physical properties of the Vertisols of Uganda except for soil texture determined during the reconnaissance soil surveys of 1958 to 1960.

2.1.2 Chemical Properties of Vertisols

Vertisols are commonly neutral to alkaline due to the high base status associated with the nature of the parent rock. However, acid Vertisols have been reported in Ethiopia with pH ranging from 5.0 to 6.2 (Desta Beyene, 1988 and Tekalign Mamo et al, 1988). In Uganda the pH of the surface horizons of those soil series classified as Vertisols ranges from 5.4 to 8.0 with a tendency of the pH to increase down the profiles (Harrop, 1960; Ollier, 1959; Ollier and Harrop, 1959; and Wilson, 1959).

The common clay minerals in Vertisols are 2:1 clays of the smectite group. Some kaolinite or other 1:1 layer silicates often occur with the smectite minerals (Le Mare, 1987). In the Vertisols of Uganda montmorillonite has been shown as the dominant clay mineral (Harrop, 1960; Ollier, 1959; Ollier and Harrop, 1959; Wilson, 1959). The organic matter and total nitrogen contents of Vertisols are often low. The phosphorus contents vary widely in relation to the parent material. Vertisols derived from granite parent materials have low to moderate phosphorus contents and low levels of available phosphorus, but those derived from basalt tend to have high phosphorus content and available phosphorus (Tekalign Mamo et al, 1988). According to Burford et al (1989), some Vertisols

in Australia have not required phosphorus inputs even after many years of continuous cropping; and Vertisols in India and Sudan require only small inputs of phosphorus. However, some Ethiopian Vertisols appear to require substantial inputs of phosphorus (Desta Beyene, 1988).

The cation exchange capacities of Vertisols are high and calcium is normally the dominant exchangeable cation. Some Vertisols have free calcium carbonate, at least in the lower horizons. The relative amounts of calcium and magnesium in Vertisols are related to the parent material from which the soils are derived (Le Mare, 1987). Where the parent material is calcareous, calcium is the dominant exchangeable cation and where the parent material is basic igneous or metamorphic rock magnesium may be as much as calcium or more. The potassium status of Vertisols is moderate to high. Magnesium-potassium antagonism may occur in Vertisols with little magnesium and much potassium.

2.2 Phosphorus Sorption in Vertisols

When phosphorus is added to soils some of it is converted into forms not readily available to plants. This phenomenon, termed fixation (Sample et al, 1980), adsorption (Bloom, 1981) and sorption (Sanchez, 1976) of phosphorus plays an important role in determining the agronomic effectiveness of phosphatic fertilizers. The process consists of transformation of soluble phosphates into less soluble compounds (Sanchez, 1976). Parfitt et al (1975) described phosphate sorption as "specific adsorption", because it involves relatively strong bonding

of the adsorbed phosphate ion, as opposed to "non-specific adsorption" of other anions such as chloride and nitrate which involve much weaker bonding. Specific adsorption of anions increases the negative charge on the adsorption site (Barrow, 1978).

A number of soil factors are known to influence phosphorus sorption in soils. These include: soil pH (Haynes, 1983; Lopez-Hernandez and Burnham, 1974b; Mokuwunye, 1975; Symth and Sanchez, 1980), ionic strength and ionic composition of the support media (Bar-Yosef et al, 1988; Ryden and Syers, 1975), the amount and type of clay minerals (Fox and Kamprath, 1970; Sree Ramulu et al, 1967; Syers et al, 1973; Upadhyay et al, 1993), exchangeable aluminum (Adepoju, 1993; Sanchez, 1976), extractable oxides of iron and aluminum (Ballard and Fiskell, 1974; Borggaard et al, 1990; Brennan et al, 1994; Jugsujinda et al, 1995; Khalid et al, 1977; Kuo, 1990; Lopez-Hernandez and Burnham, 1974a; Mubiru and Karathanasis, 1994; Yuan and Lavkulich, 1994), calcium carbonate, exchangeable calcium and magnesium in calcareous soils (Larsen and Widdowson, 1970; Sanchez, 1976) and specific surface area of the soil mineral surface (Juo and Fox, 1977; Wild, 1988).

The relative importance of these factors vary from soil to soil, and according to Lopez-Hernandez and Burnham (1974a) these properties are themselves

interrelated. The overall amount of phosphorus sorbed is therefore a function of the chemical and mineralogical properties of the soil.

Three mechanisms of phosphorus sorption proposed by Ryden et al (1977) are:

- (i) chemisorption at the protonated surface sites
- (ii) chemisorption by replacement of surface hydroxyls
- (iii) a more physical sorption of phosphate as a potential-determining ion.

Chemisorption involves ligand exchange reactions at the original sorbent surface where a pair of singly coordinated OH groups are replaced by phosphate resulting in a binuclear co-ordination. A potential-determining ion is one which when adsorbed on a surface changes the potential of the surface and this can be neutralised by further adsorption of ions of the opposite charge. When chemisorption is complete the nature of the surface of the sorbent changes. The more physical potential-determining sorption occurs on the modified sorbent surface and is of both a "common" and "non-common" ion type relative to the modified surface of the sorbent (Ryden et al, 1977).

Another process of phosphorus sorption is that described by Kuo and Lotse (1972). They regarded the phosphorus adsorption process in a water suspension of calcium carbonate crystallites as competition where phosphate may replace

adsorbed water molecules, bicarbonate ions or hydroxyl ions; the relative adsorption strength of the phosphate ions and other anions depending upon the solubility of the compound formed with the surface calcium ions.

The residual value of the sorbed phosphorus depends on the amount of added phosphorus, the nature of fixation products, the soil physical and chemical properties (Ayodele and Agboola, 1981), and the surface activity of the oxides and hydroxides. The adsorbed phosphate may be highly available to plants when the surface is nearly saturated but when a small amount of phosphate is retained by a large amount of amorphous oxides and hydroxides, the adsorbed phosphate may not be easily available to plants (Hsu, 1964).

In Vertisols phosphorus appears to be weakly held on the adsorbing surfaces and so can be easily extracted by plants (Le Mare, 1987). This partly explains the lack of response to phosphorus application even in some Vertisols low in available phosphorus as determined by the Olsen or Bray I methods (Burford et al, 1989). Availability of phosphorus in Vertisols has also been shown to fluctuate with season, the availability being higher in the wet season than in the dry season, apparently because of the influence of water on phosphorus availability in the soils (Katyal and Venkatramayya, 1983). Flooding and draining also affects availability of phosphorus in Vertisols. Under flooded condition iron is reduced

so releasing phosphorus but when the soils are drained iron is oxidised leading to formation of poorly crystalline ferric hydrous oxides and these adsorb phosphorus so reducing its availability (Le mare, 1987).

Different strategies have been used to manage phosphorus fixation. In soils with moderate fixation capacity small amounts of superphosphate can be broadcast and incorporated into the topsoil or banded once a year (Sanchez, 1976). In soils that fix large amounts of phosphorus two main strategies have been advocated for (Sanchez and Uehara, 1980). First is the high input strategy which consists of massive initial application of phosphorus. The main advantages of this strategy are that: (i) the residual effect occurs over a long time, (ii) there is a decrease in phosphorus fixation capacity of the soil, (iii) an improvement of the soil physical properties, (iv) an increase in soil pH and (v) an increase in cation exchange capacity (CEC). Adsorption of phosphorus increases CEC by displacing the zero point charge to a lower value, making the surface charge more negative. The main limitations of this strategy are the high initial investment and adequate financing required, a stable land tenure and high-value crops.

Second is the low input strategy that has a number of components: (i) moderate banded application of phosphorus to increase the efficiency of phosphorus fertilization and the use of cheaper sources of phosphorus such as phosphate rock

for direct application, (ii) decreasing phosphorus fixation capacity with relatively cheaper amendments such as lime or silicates. The beneficial effect of liming acid soils to pH of about 5.5 has been attributed to the precipitation of exchangeable and hydroxy aluminum as aluminum hydroxides which fix less phosphorus and the lower bonding energy between sorbed phosphorus and oxides surfaces (Kamprath and Foy, 1971); (iii) decreasing crop requirement by selecting varieties or species tolerant to low levels of available phosphorus in the soils. The soil properties and economic factors, should therefore be considered in selection of the strategy to use.

Generally, literature on phosphorus sorption in Vertisols is lacking. In comparison with other soil Orders, Vertisols tend to adsorb less phosphate and the few data available indicate that phosphate is probably weakly held in Vertisols (Le Mare, 1987). However, the amount of phosphate adsorbed by some Greek Vertisols were similar to those adsorbed by many acid, kaolinitic soils (Nychas and Kosmas, 1984). In calcareous Vertisols of Spain short-term phosphorus sorption was highly correlated with citrate-dithionite-bicarbonate iron and clay content but long-term sorption of phosphorus was mostly affected by calcium carbonate with iron oxides contributing less to that process (Solis and Torrent, 1989a). In Ethiopian Vertisols there were positive correlations between phosphorus sorption and organic matter content, extractable iron and aluminum

(Tekalign Mamo et al, 1988). The correlation of fixed phosphorus with clay content or pH was poor.

From the above it appears that the factors that influence phosphorus sorption in Vertisols vary from place to place. It is therefore not possible to make a generalisation on the main soil factors that influence phosphorus sorption in Vertisols, necessitating determination for each place.

Information available indicates that the role of organic matter in phosphorus sorption in soils differ. In a Typic Dystrandept organic anions did not affect phosphorus sorption (Appelt et al, 1975b). Citrate and oxalate anions decreased, but acetate increased phosphorus sorption in kaolinite and montmorillonite (Kafkafi et al, 1988). Sibanda and Young (1986) reported decrease in phosphorus sorption on goethite and gibbsite after application of organic matter.

There are few studies on the effects of organic matter application on phosphorus sorption in Vertisols. Sah and Mikkelsen (1989) found that addition of organic matter in form of cellulose in an Entic Chromoxerert increased phosphorus sorption. However, it is possible that addition of organic matter may increase, decrease or not affect phosphorus sorption in Vertisols like in other soils (Sah and Mikkelsen, 1989). This is because the effects of organic matter on phosphorus

sorption in soils or synthetic oxides has been shown to depend on the type of organic anions added or produced from the organic materials added in soils (Earl et al, 1979; Kafkafi et al, 1988); phosphorus content of the organic material added in the soil (Singh and Jones, 1976); the concentration of phosphorus in solution (Appelt et al, 1975b); and the order of organic matter addition, i.e. before, after or with phosphorus (Violante et al, 1991).

2.3 Phosphorus fractions in Vertisols

The phosphorus in soils can be classified as organic or inorganic depending on the nature of the compound in which it occurs (Tisdale and Nelson, 1966; Lindsay et al, 1989). The inorganic fraction occurs in numerous combinations with aluminum, calcium, iron and other cations. The organic fraction is found in humus and other organic materials. The content of inorganic phosphorus in most soils is always higher than that of organic phosphorus except in predominantly organic soils. In mineral soils the organic phosphorus content is usually higher in the surface than subsoil because of the differential accumulation of organic matter.

The chemical forms of organic phosphorus that have been identified in soils include inositol phosphate esters, phospholipids, nucleic acids, sugar phosphates

and derivatives of phosphonic acid (Thomas and Bowman, 1966; Wild, 1988). The solid inorganic forms of phosphorus are usually divided into three active and two inactive fractions (Sanchez, 1976). The active fractions are grouped into calcium-bonded (Ca-P), aluminum-bonded (Al-P) and iron-bonded (Fe-P) phosphorus. The solubility and availability of phosphorus in these fractions differ. Calcium-bonded phosphorus is more soluble than Al-P which in turn is more soluble than Fe-P. The transformation of one form of the active inorganic phosphorus fraction into another is partly controlled by the soil pH. According to De Geus (1973) the availability of Al-P and Fe-P decrease as the soil becomes more acidic, while that of Ca-P shows the reverse trend. The Fe-P, Al-P and Ca-P are also referred to as non-occluded phosphorus and represent phosphate ions sorbed at the surfaces of iron and aluminum oxides and hydrous oxides, and calcium carbonate (Walker and Syers, 1976).

The inactive fractions of inorganic phosphorus are the occluded and reductant-soluble forms. The occluded phosphorus consists of Al-P and Fe-P compounds surrounded by an inert coat of another material, especially coatings and concretions of oxides and hydrous oxides of iron and aluminum, that prevent reactions of these phosphates with soil solution. The reductant-soluble forms are covered by a coat that may be partially or totally dissolved under anaerobic conditions.

Like for other soils, the amounts of Ca-P, Al-P and Fe-P in Vertisols are related to the soil reaction. In calcareous Vertisols of Spain, Solis and Torrent (1989b) found that Ca-P fraction was the most abundant and the non-occluded Al-P and Fe-P were present in small amounts.

There are a number of methods for fractionation of phosphorus in soils but they can basically be divided into two categories:

(i) those that identify phosphorus bound onto inorganic constituents of the soil matrix such as the methods of Petersen and Corey (1966) and Williams et al (1967, 1971). Basically these methods involve sequential extraction of phosphorus in soil with NH_4F to extract Al-bound phosphorus, NaOH to extract Fe-bound phosphorus, citrate-dithionite-bicarbonate to extract 'occluded' forms of phosphorus, and HCl or H_2SO_4 to extract Ca-bound phosphorus.

(ii) those that distinguish labile and more stable forms of inorganic phosphorus (Pi) and organic phosphorus (Po) such as the methods of Hedley et al (1982), Okalebo et al (1993), Tiessen and Moir (1993), and Beck and Sanchez (1994). These methods remove inorganic and organic phosphorus of increasing chemical stability in terms of soil phosphorus fertility (Sharpley et al, 1987) and therefore give soil phosphorus fractions which vary in the extent of their availability to growing plants. The soil phosphorus is fractionated into increasingly recalcitrant organic and inorganic pools by sequentially extracting with anion exchange resin

to remove available phosphorus (Resin-Pi); 0.5 M NaHCO_3 , pH 8.5 to remove labile phosphorus pool (bicarbonate-Pi and Po); 0.1 M NaOH to remove slow phosphorus pool (NaOH-Pi and Po); 0.01 M NaOH after sonication to remove occluded phosphorus (NaOH sonication-Pi and Po); 1.0 M HCl to remove weatherable mineral phosphorus (HCl-Pi); and digestion with concentrated H_2SO_4 to remove passive or residual phosphorus (residual Pi and Po).

In terms of availability to plants resin-P is considered the most plant available phosphorus fraction followed by bicarbonate-P. Hydroxide extractable phosphorus has lower plant availability and is associated with aluminum and iron phosphates, and phosphorus held in internal surfaces of soil aggregates (Williams et al, 1980; Yang and Jacobsen, 1990). HCl-Pi is largely Ca-bound phosphorus associated with apatite-minerals and occluded phosphorus (Bowman et al, 1978). Cross and Schlesinger (1993) considered bicarbonate-Po, NaOH-Po and sonicate-Po as biological phosphorus; and resin-Pi, bicarbonate-Pi, NaOH-Pi, sonicate-Pi, HCl-Pi and the Po and Pi in the residual fraction as geochemical phosphorus.

Studies done to relate the inorganic phosphorus fractions (Al-P, Ca-P and Fe-P) to indices of phosphorus availability or phosphorus uptake and yield of crops have shown that these fractions vary considerably as sources of phosphorus to crops both in soils and in time (Novias and Kamprath, 1978; Singh et al, 1966;

Tripathi et al, 1970). This has been attributed to differences in chemical composition of each fraction, contents of aluminum, iron, calcium as well as soil pH (Singh et al, 1966; Susuki et al, 1963; Volk and McLean, 1963). In North Carolina soils Al-P was the principal source of phosphorus removed by crops in sandy soils but in clayey soil both Al-P and Fe-P supplied equal amounts of phosphorus to crops Novias and Kamprath, 1978). In a clay loam Ca-P and Fe-P were the main source of phosphorus for the first crop of alfalfa but Fe-P was the main source of phosphorus for the second and third crop (Singh et al, 1966). In Indian soils Al-P was the dominant fraction contributing to labile phosphorus extracted by Bray I extractant, Olsen extractant removed mainly Al-P and Fe-P, Ca-P made insignificant contribution to labile phosphorus estimated by Olsen and isotopic exchangeable phosphorus methods, apparently because of occlusion in calcium carbonate matrices (Tripathi et al, 1970). In South Dakota there was negative correlation between Ca-P and Bray I phosphorus but correlations of Al-P and Fe-P with Bray I and Olsen phosphorus were positive and significant (Westin and Buntley, 1966).

Information on the relationship between Al-P, Ca-P, Fe-P and available, labile and slow phosphorus pools is scanty. According to Tandon and Kurtz (1968) labile phosphorus is related to Al-P and Ca-P. Yang and Jacobsen (1990) studied the relationship between resin-P, bicarbonate-P, NaOH-P, HCl-P and available

phosphorus determined by Olsen method and phosphorus uptake, and resin-P was highly correlated with Olsen-P and plant uptake. Phosphorus uptake by foxtail millet correlated with labile phosphorus (Sattell and Morris, 1992).

Literature available therefore indicates that the phosphorus status and sorption characteristics of Vertisols vary between and within countries. However, little is known about the amounts, nature and behaviour of phosphorus in the Vertisols of Uganda.

CHAPTER THREE

MATERIALS AND METHODS

3.1 Site, soil and profile description

The soils for the study were collected from areas known to have Vertisols and that had no previous phosphorus fertilizer history. The areas were Kamutur in Kumi district, Olweny Swamp Rice Irrigation Project in Lira district and Sironko in Mbale district. The soils of Kamutur and Sironko belong to the Sebei and Siroko soil series respectively. These soil series have been described elsewhere (Ollier and Harrop, 1959). The soil of Olweny was identified as belonging to undifferentiated alluvial clay (Ollier, 1959) but recent work by Euroconsult / Serefaco Consultants Ltd (1992) divided the parent materials for the soils in Olweny Swamp Rice Irrigation Project into alluvial, alluvial fans and residual materials from basement complex.

In each area a sampling unit was demarcated for use in site and profile description, and collection of soil samples for the different studies that had been planned. The sampling unit was about 6 hectares under fallow in Kamutur; 5 hectares block under rice in Olweny Swamp Rice Irrigation Project and about 4 hectares under fallow in Sironko. Each area was considered as a sampling unit

because of the uniformity in vegetation and past management practices. Profile description was done in each area to determine the soil type. Site characterisation and profile description coincided with the rainy season and could not be delayed to the dry season because of time limit for the research. The general characteristics of the soil profiles that were studied and recorded included soil colour, texture, structure, presence of slickensides or pressure faces and consistence (Seghal and Bhattacharjee, 1987). The soil colour (moist soil) was determined using the Munsell soil colour charts; texture was determined using the 'feel' method by rubbing the soil between the thumb and fingers; consistence was determined by observing how the soil develops a continuous ribbon when moulded between the thumb and fingers. Samples were taken from each profile for laboratory analysis.

In each sampling unit soil samples were randomly collected from 0-20 cm depth for the main study and taken to Serere Agricultural and Animal Production Research Institute (SAARI) for air-drying at room temperature. The soil samples were taken using an auger with a core that had an internal diameter of 10.2 cm. Three hundred fifty cores were taken from each unit and mixed together using a rotating drum and about 80 kg of fresh soil was taken by quarter-sampling. After drying, the soil from each unit was ground, sieved through 2 mm, mixed again using a rotating drum, bagged in nylon bags and transported to Makerere

University for physico-chemical analysis and subsequent studies on phosphorus status and sorption characteristics.

The physico-chemical properties of the profile and composite samples were determined using standard laboratory methods. Available phosphorus was determined by the Bray I method (IITA, 1979), particle size analysis by the hydrometer method, and soil pH by the glass electrode in soil suspension of soil:water ratio of 1:2.5 (Okalebo et al, 1993). Total nitrogen was determined by the Kjeldahl method and organic carbon by oxidation with sulphuric acid and aqueous potassium dichromate mixture then titrating against ferrous ammonium sulphate solution (Okalebo et al, 1993). Exchangeable bases in the soils were extracted with neutral ammonium acetate. Magnesium in the extracts was determined with the atomic absorption spectrophotometer while calcium, potassium and sodium were determined by flame photometry (Okalebo et al, 1993). Total iron and aluminum oxides were extracted with citrate-dithionite-bicarbonate (CDB) and the amorphous (short-range order) oxides of the same elements were extracted with ammonium oxalate (IITA, 1979). Iron and aluminum in the extracts were determined by orthophenanthroline method and the modified aluminon method respectively (IITA, 1979). An estimate of the crystalline oxides of iron and aluminum was obtained by subtracting amorphous oxides from CDB-extractable oxides (Ryden and Syers, 1975).

3.2 Sorption characteristics

The method outlined by Okalebo et al (1993) was used in phosphorus sorption studies. Three gramme duplicate samples of soils were put in 50 ml tubes and 30 ml of 0.01 M CaCl_2 containing graded concentrations of phosphate (0-200 ppm P) in form of $\text{Ca}(\text{H}_2\text{PO}_4)_2$ were added. Calcium chloride at 0.01 M was used as the support medium because it gives clear extracts (Fox and Kamprath, 1970) and it has been reported that cation exchange is minimised by the use of calcium and chloride at this concentration has no specific replacing power (Ryden and Syers, 1975). Three drops of toluene were added in each tube to suppress microbial activity. The samples were then equilibrated for 6 days, during which they were shaken in a reciprocal shaker for a 30 minute period twice a day, in the morning and afternoon. Room temperatures were measured during the shaking period and the mean was taken as the equilibration temperature. At the end of the 6 days the samples were filtered through Whatman No 42 filter paper and 10 ml of the filtrate (equilibrium solution) was pipetted for colorimetric determination of phosphorus as described by Okalebo et al (1993). The amount of phosphorus sorbed was calculated as the difference between the added phosphorus and the phosphorus in the equilibrium solution. The phosphorus sorption isotherms for the soils were constructed by plotting the equilibrium phosphorus concentration, expressed in parts per million (ppm), on x-axis against phosphorus sorbed (ppm)

on y-axis. The standard phosphorus requirements (amounts of phosphorus sorbed at equilibrium phosphorus concentration of 0.2 ppm) of the soils were calculated from the equations for the sorption isotherms.

To obtain the phosphorus sorption maxima and constants of bonding energy the sorption data were plotted according to the linear (conventional) form of the Langmuir equation (Rennie and McKercher, 1959; Syers et al, 1973):

$$C/(x/m) = 1/Kb + C/b,$$

where C = the equilibrium concentration of phosphorus (mg/L),

x = the quantity of phosphorus sorbed (mg),

m = the quantity of soil used (g),

K = bonding energy constant,

b = phosphorus sorption maximum (mg/kg).

The Langmuir equation was chosen over the other equations for describing phosphorus sorption because it provides adsorption maximum and a coefficient related to bonding energy (Kuo, 1988; Syers et al, 1973). The phosphorus sorption maxima and constants related to bonding energy were calculated using the above equation as described by Syers et al (1973); where a plot of $C/(x/m)$ vs C was constructed, then sorption maxima obtained as the reciprocal of the gradient and constants related to bonding energy as gradient divided by intercept.

3.3 Effects of organic matter application on phosphorus sorption and availability of native P in the soils

Organic matter was used in an incubation experiment to study its effects on phosphorus sorption in the soils. The sources of organic matter were cellulose and starch. These materials were used by Sah and Mikkelsen (1989) in a similar study, to avoid the difficulty in partitioning phosphorus from the soil and that from animal manure or crop residues which could have been used as organic matter as well. Symth and Sanchez (1980) found that phosphorus application reduced phosphorus sorption, so addition of phosphorus in the animal manure or plant residues could affect phosphorus sorption. The rates of organic matter were 10 and 20 g (85% cellulose + 15% starch) per kg soil, represented as M_1 and M_2 respectively. A control (C) of no soil amendment was also included. These ratio and rates were also used by Sah and Mikkelsen (1989) in a similar study.

One hundred gramme samples of each soil were mixed with the treatments, put in polythene bags, moistened to about field capacity, sealed and incubated at room temperature for 30, 60 and 90 days. Each treatment was replicated three times for each period of incubation and arranged in a completely randomized design. At the end of each incubation period the soils were air-dried and three gramme duplicate samples of the soils were then equilibrated with 0.01 M CaCl_2 .

To remove exchangeable calcium, one gramme duplicate samples of the soils were first washed with 1 N NH_4Cl by shaking for 30 minutes, centrifuging at 2000 rpm for 10 minutes and discarding the supernatant. The inorganic phosphorus fractions in the soil matrix were then sequentially extracted with 0.5 N NH_4F of pH 8.2 by shaking for one hour and centrifuging at 2000 rpm for 10 minutes; 0.1 N NaOH by shaking for 17 hours, centrifuging at 2000 rpm for 15 minutes, decanting the supernatant solution and adding 5 drops of concentrated H_2SO_4 to the supernatant solution to flocculate organic matter; 0.3 N sodium citrate plus solid sodium dithionite and shaking for 5 minutes, heating the samples in the tubes in a water bath at 75-80 °C for 15 minutes, shaking again for 5 minutes and centrifuging at 2000 rpm for 10 minutes; and 0.5 N H_2SO_4 by shaking for one hour and centrifuging at 2000 rpm for 10 minutes. These extracted aluminum-bonded (Al-P), iron-bonded (Fe-P), reductant-soluble (Red-P) and calcium-bonded (Ca-P) phosphorus respectively. After each stage of extraction the soil residue was washed twice with saturated sodium chloride solution by bringing the soil in suspension, centrifuging at 2000 rpm for 5 minutes and decanting to eliminate interactions between the different extractants. The phosphorus in the extracts was determined colorimetrically.

3.5 Effects of phosphorus application on the inorganic phosphorus fractions in the soils

To study the changes in the inorganic phosphorus fractions after application of phosphorus fertilizers an incubation study was conducted. In this experiment only the soils from Kamutur and Olweny Rice Scheme were used because the results from the initial characterisation of the soils showed that Sironko soil had adequate available phosphorus, and was not likely to produce significant responses. Jackson (1958) stated that if the available phosphorus extracted by Bray I method is more than 20 ppm P the available phosphorus in the soil should be considered adequate.

The fertilizer used was single superphosphate (8.2% P). The rates of phosphorus application were: 0, 7.5, 15, 22.5 and 30 mg P kg⁻¹ soil. These rates translate to 0, 15, 30, 45, 60 kg P/ha respectively, and were chosen to fall within the range of phosphorus rates used in phosphorus fertilizer experiments reported in countries where crop response to phosphorus application in Vertisols have been studied (Desta Beyene, 1988; Katyal et al, 1987).

One hundred gramme samples of the soils were mixed with the treatments, put in polythene bags, moistened to about field capacity, sealed and incubated at

room temperature for 30, 60 and 90 days. The experimental design was a completely randomized design and the treatments were replicated three times for each incubation period. At the end of each incubation period the soils were air-dried and the inorganic phosphorus fractions in the soils were then determined as described in section 3.4.

The data collected on the inorganic phosphorus fractions were subjected to analysis of variance using MSTATC computer package. Mean separation was by least significant difference (LSD).

CHAPTER FOUR

RESULTS

4.1 Site, profile and soil description and identification

Site, profile and soil description are presented in Tables 1a and 1b. The soils were generally dark coloured throughout the profiles. In the three soils, the hue of the surface horizon was 10YR. In Kamutur and Olweny soils the texture was clay throughout the profiles while in the Sironko soil it was clay loam in the surface horizons. There were smooth shiny faces in the sub-soil horizon in all the profiles. The structure became massive down the profiles.

The results for some of the physico-chemical characteristics of the soil profiles are presented in Table 2. The soil of Sironko, which was better drained, had the lowest amount of clay. In all the profiles clay content increased down the profile. The soil pH in the profiles ranged from 6.0 to 7.2, the surface soil being weakly acid. Organic carbon, total nitrogen and available phosphorus (Bray I P) decreased down the profiles. Exchangeable calcium increased down the profiles. In general the level of exchangeable calcium and magnesium were highest in the profile of Kamutur soil

Table 1. Results of soil site and profile description.

(a) General information.

Site characteristics	Site		
	Kamutur	Olweny	Sironko
Location	1° 22' N ; 34° 12' E	1° 59' N ; 33° 1' E	1° 14' N ; 34° 15' E
Land use	grazing livestock	paddy rice production	annual crop production
Relief	extensive flat plain	level site with small mounds built by worms	very gentle slope
Vegetation ¹	<i>Hyparrhenia</i> / <i>Themeda</i> spp grassland	<i>Echinochloa pyramidalis</i>	<i>Imperata cylindrica</i> / <i>Hyparrhenia rufa</i>
Parent material ²	alluvium derived from mixed volcanic / metamorphic rocks	alluvium	colluvium derived from volcanic rocks
Drainage ³	poor	poor to imperfect	moderately well drained

1 = Vegetation from land that had not been cropped for the last 5 years.

2, 3 = Sources: Ollier and Harrop (1959) for Kamutur and Sironko soils and Euroconsult/Serfaco Consultants Ltd (1992) for Olweny soil.

(b) Morphological characteristics.

Soil	Horizon	Depth (cm)	Colour	Texture	Structure	Slickensides/ pressure faces	Consistence
Kamutur	Surface	0-23	10YR3/1	clay	weak, blocky	-	sticky
	Sub-surface	23-55	2.5YR3/0	clay	massive	smooth vertical faces	very sticky
	Sub-soil	55-102	2.5YR3/1	clay	massive	smooth vertical faces	very sticky
Olweny	Surface	0-25	10YR3/1	clay	weak, blocky	-	sticky
	Sub-surface	25-62	10YR4/1	clay	massive	few shiny faces	very sticky
	Sub-soil	62-100	2.5YR4/0	clay	massive	few slickensides	very sticky
Sironko	Surface	0-20	10YR4/2	clay loam	blocky	-	slightly sticky
	Sub-surface	20-48	10YR3/2	clay	massive	-	sticky
	Sub-soil	48-105	2.5YR3/0	clay	massive	few shiny faces	sticky

Table 2. Some of the physico-chemical characteristics of the soil profiles.

Soil	Depth (cm)	Silt (%)	Clay (%)	pH (H ₂ O)	Organic C (%)	Total N (%)	Bray I P (ppm)	Exchangeable bases (me/100g)				CEC (me/100g)	Base saturation (%)
								Ca	Mg	K	Na		
Kamutur	0-23	15	49	6.4	1.92	0.22	11.0	9.8	6.3	0.7	3.4	36.5	55.3
	23-55	10	60	6.9	1.16	0.08	8.5	12.5	7.8	0.7	2.7	40.6	58.4
	55-102	8	64	7.2	0.86	0.03	7.8	14.0	7.0	0.8	3.1	38.3	66.8
Olweny	0-25	10	53	6.4	1.66	0.18	6.4	9.6	2.4	0.4	3.6	27.8	57.6
	25-62	11	60	6.6	0.60	0.09	6.0	13.3	6.3	0.6	3.8	34.0	66.7
	62-100	12	69	6.8	0.62	0.06	6.0	14.2	5.2	0.4	3.8	40.5	58.3
Sironko	0-20	9	36	6.2	1.76	0.17	39.0	6.7	1.8	0.8	3.8	27.2	48.2
	20-48	10	50	6.4	1.34	0.08	38.6	13.0	1.9	0.8	3.2	37.4	50.5
	48-105	12	60	6.9	0.85	0.03	36.0	13.6	1.8	0.9	4.0	35.3	57.5

and lowest in that for Sironko soil. Exchangeable potassium was lowest in the profile for Olweny soil and highest in Sironko soil. Exchangeable sodium was lowest in Kamutur soil and highest in Sironko soil.

Some of the physico-chemical characteristics of the composite soils used in the main study are shown in Table 3. The soils were slightly to very slightly acidic, with Sironko soil having the lowest pH and Olweny soil the highest. The textural class for the soils from Olweny and Kamutur was clay and that of the soil from Sironko clay loam. The organic matter and total nitrogen contents were moderate. The amounts of citrate-dithionite-bicarbonate (CDB) extractable aluminum oxides were greater than CDB iron oxides in all the soils and the oxalate extractable iron oxides were greater than amorphous aluminum oxides in all the soils. The total amorphous oxides was highest in Sironko soil, followed by Kamutur soil and soil from Olweny had the least amount of amorphous oxides. The levels of CDB and oxalate extractable iron oxides were lowest in the soil from Olweny and CDB and oxalate extractable aluminum oxides were highest in this soil. Available phosphorus was highest in the soil from Sironko and lowest in the soil from Olweny. The levels of exchangeable bases in Kamutur soil was $\text{Ca}^{2+} > \text{Mg}^{2+} > \text{Na}^+ > \text{K}^+$, but for Olweny and Sironko soils the order was $\text{Ca}^{2+} > \text{Na}^+ > \text{Mg}^{2+} > \text{K}^+$.

Table 3: Physico-chemical characteristics of the composite soils.

Properties	Soil		
	Kamutur	Olweny	Sironko
Bray I P (ppm)	11.6	6.6	39.5
pH	6.5	6.6	6.3
Total N (%)	0.20	0.20	0.13
Organic C (%)	1.94	1.70	1.81
Exchangeable bases			
(me / 100 g) : Ca	9.6	8.9	6.2
Mg	5.9	2.3	1.6
K	0.75	0.37	0.83
Na	3.4	3.5	3.7
Iron oxides (%): CDB*	1.25	0.45	0.74
Oxa*	0.31	0.28	0.43
Cry*	0.94	0.17	0.31
Aluminum oxides: CDB*	1.50	1.83	1.67
Oxa*	0.18	0.22	0.31
Cry*	1.32	1.61	1.36
Clay (%)	50	58	36
Silt (%)	6	10	22
CEC (me/100g)	36.3	28.0	27.0

CDB* = citrate-dithionite-bicarbonate extractable oxides.

Oxa* = oxalate extractable oxides.

Cry* = crystalline oxides..

According to the classification of Olsen and Sommers (1982) for available phosphorus, the available phosphorus is low in Olweny soil, medium in soil from Kamutur and high in Sironko soil. In these guidelines the available phosphorus determined by Bray I method using soil:solution ratio of 1:7 is rated as: <3 ppm P, very low; 3<7 ppm P, low; 7-20 ppm P, medium; and >20 ppm, high.

4.2 Sorption characteristics

The phosphorus sorption isotherms of the non-treated soils are given in Figure 1. The soils differ in their ability to sorb added inorganic phosphorus. The extent of phosphorus sorption in the soils was in the order: Kamutur > Olweny > Sironko.

When the sorption data were plotted according to the conventional Langmuir equation, two straight lines were obtained for Kamutur and Olweny soils and one for Sironko soil over the same range of phosphorus concentration used (Figure 2). For the soils where two straight lines were obtained, the first was corresponding to the lower equilibrium phosphorus concentrations (region I) and the second to the higher equilibrium phosphorus concentrations (region II).

The Langmuir sorption maxima, bonding energy constants and standard phosphorus requirements (SPR) of the soils are presented in Table 4. The SPR was lowest (8.62 ppm P) in Sironko soil and highest (46.61 ppm P) in Kamutur soil. In Kamutur and Olweny soil the sorption maxima and bonding energy constants for region I were higher than those for region II.

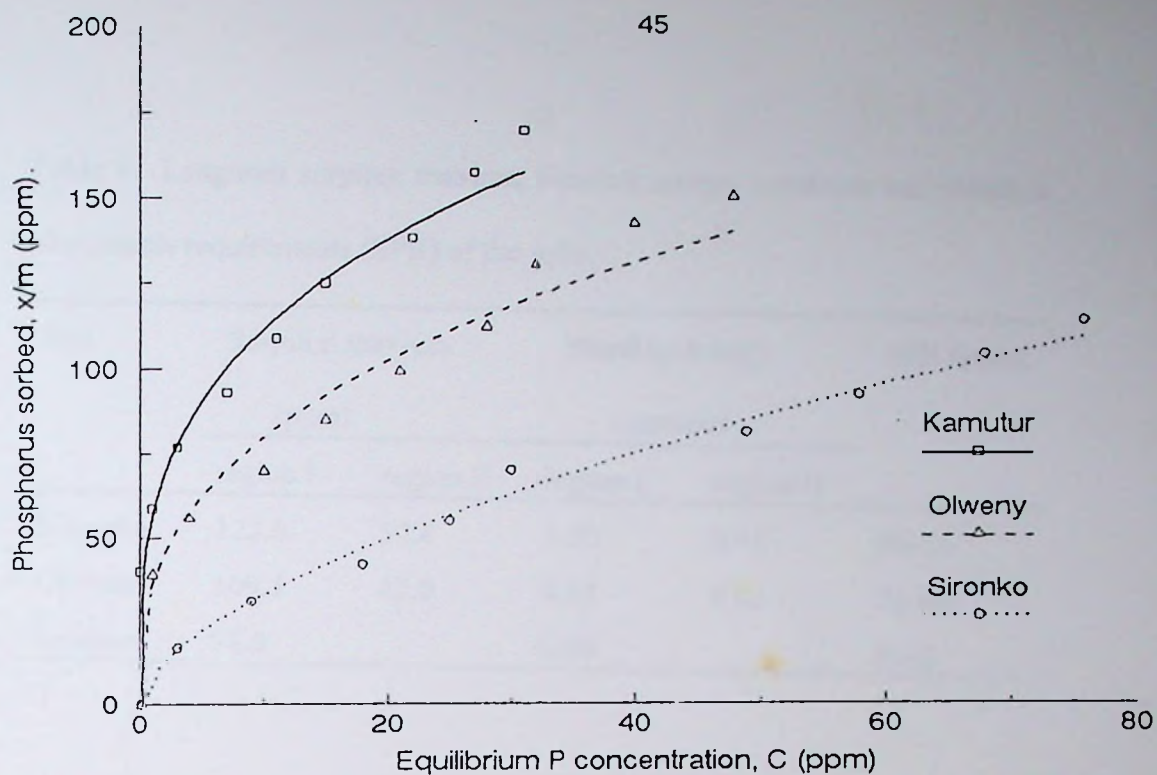


Figure 1. Phosphorus sorption isotherms of the soils before incubation.

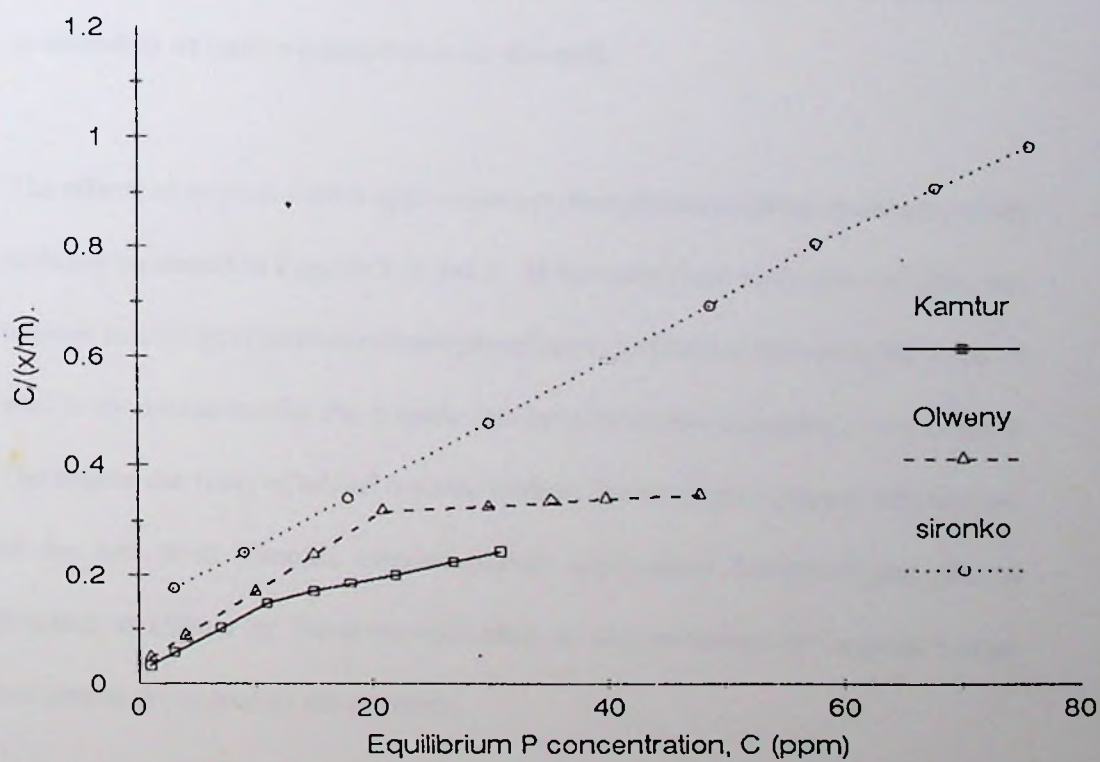


Figure 2. Langmuir plots for P sorption in the soils before incubation.

Table 4. Langmuir sorption maxima, bonding energy constants and standard phosphorus requirements (SPR) of the soils.

Soil	Sorption maxima		Bonding energy		SPR (ppm)
	(ppm)		constants		
	region I	region II	region I	region II	
Kamutur	122.6	52.4	0.50	0.11	46.61
Olweny	109.5	42.0	0.37	0.03	36.08
Sironko	98.0		0.08		8.62

4.3. Effects of organic matter application on phosphorus sorption and availability of native phosphorus in the soils

The effects of organic matter application on phosphorus sorption isotherms of the soils are presented in Figures 3 ,4 and 5. In the soils from Kamutur and Olweny, organic matter application increased phosphorus sorption as shown by the upward shift in the isotherms for the organic matter treatments compared to the control. The higher the level of added organic matter, the more phosphorus was sorbed. In the soil from Sironko, organic matter application decreased phosphorus sorption as shown by the downward shift in the isotherms for organic matter treatments compared to the controls.

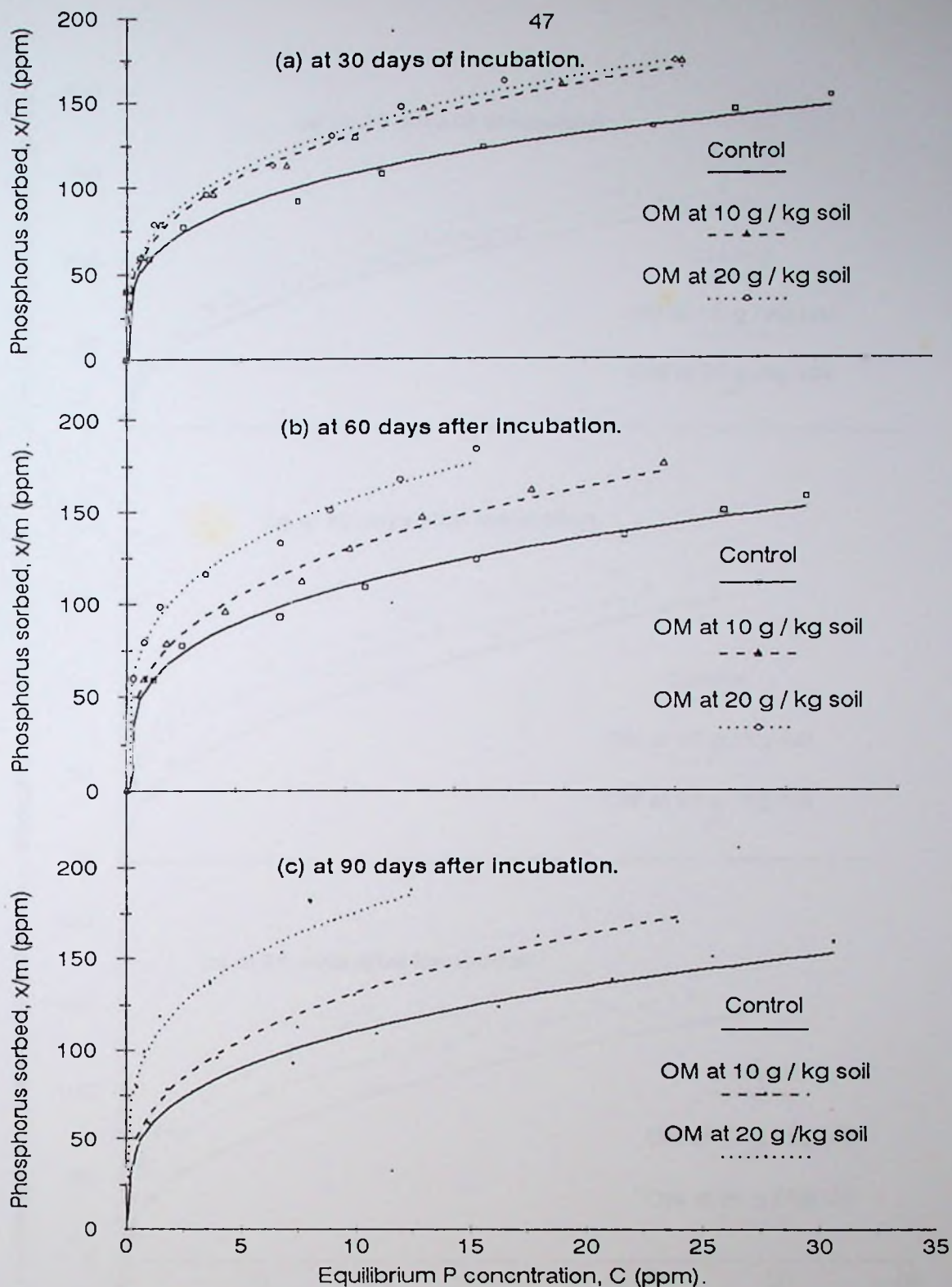


Figure 3. Effects of organic matter application on phosphorus sorption isotherms of Kamutur soil.

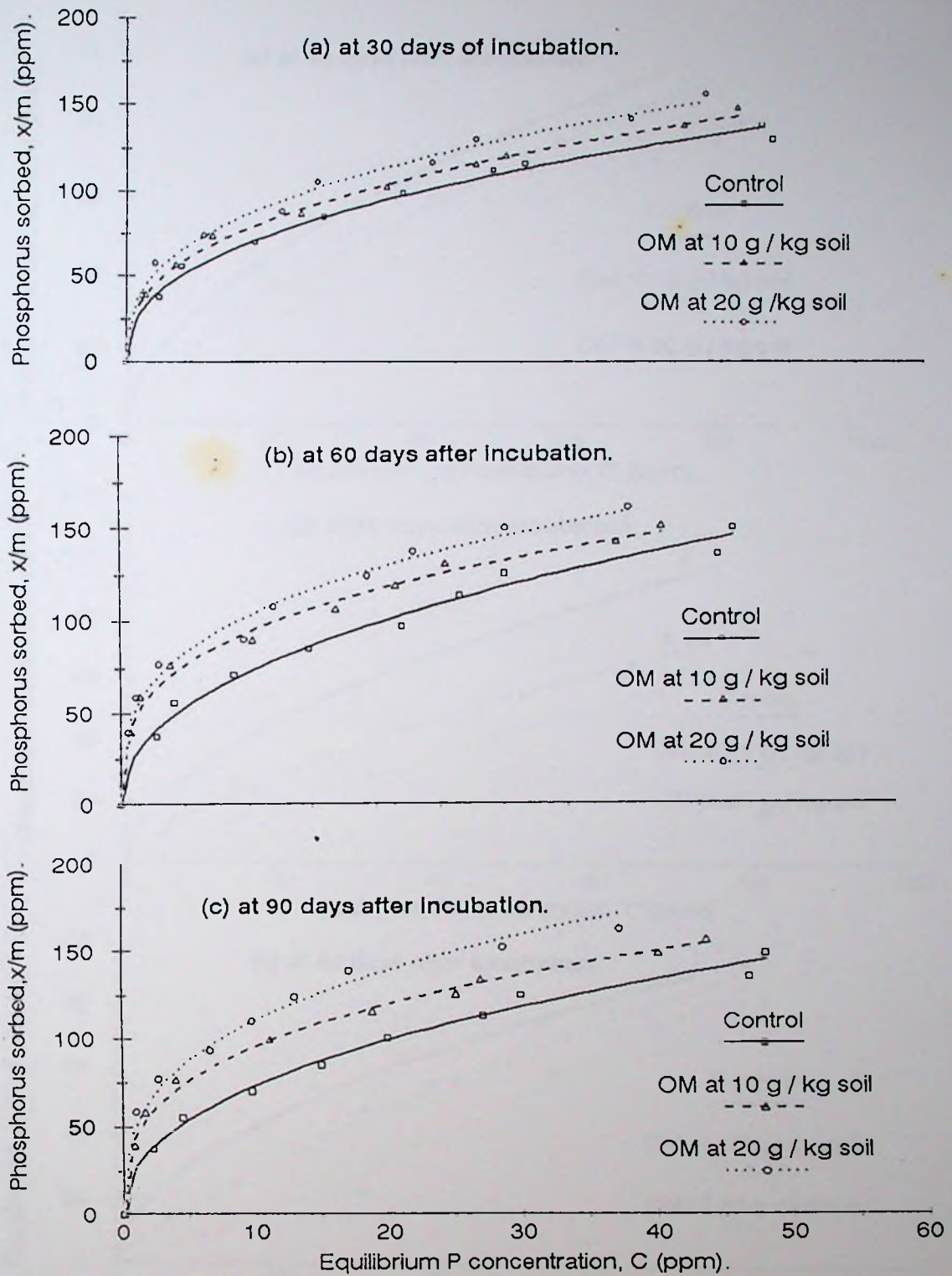


Fig. 4. Effects of organic matter application on phosphorus sorption isotherms of Olweny soil.

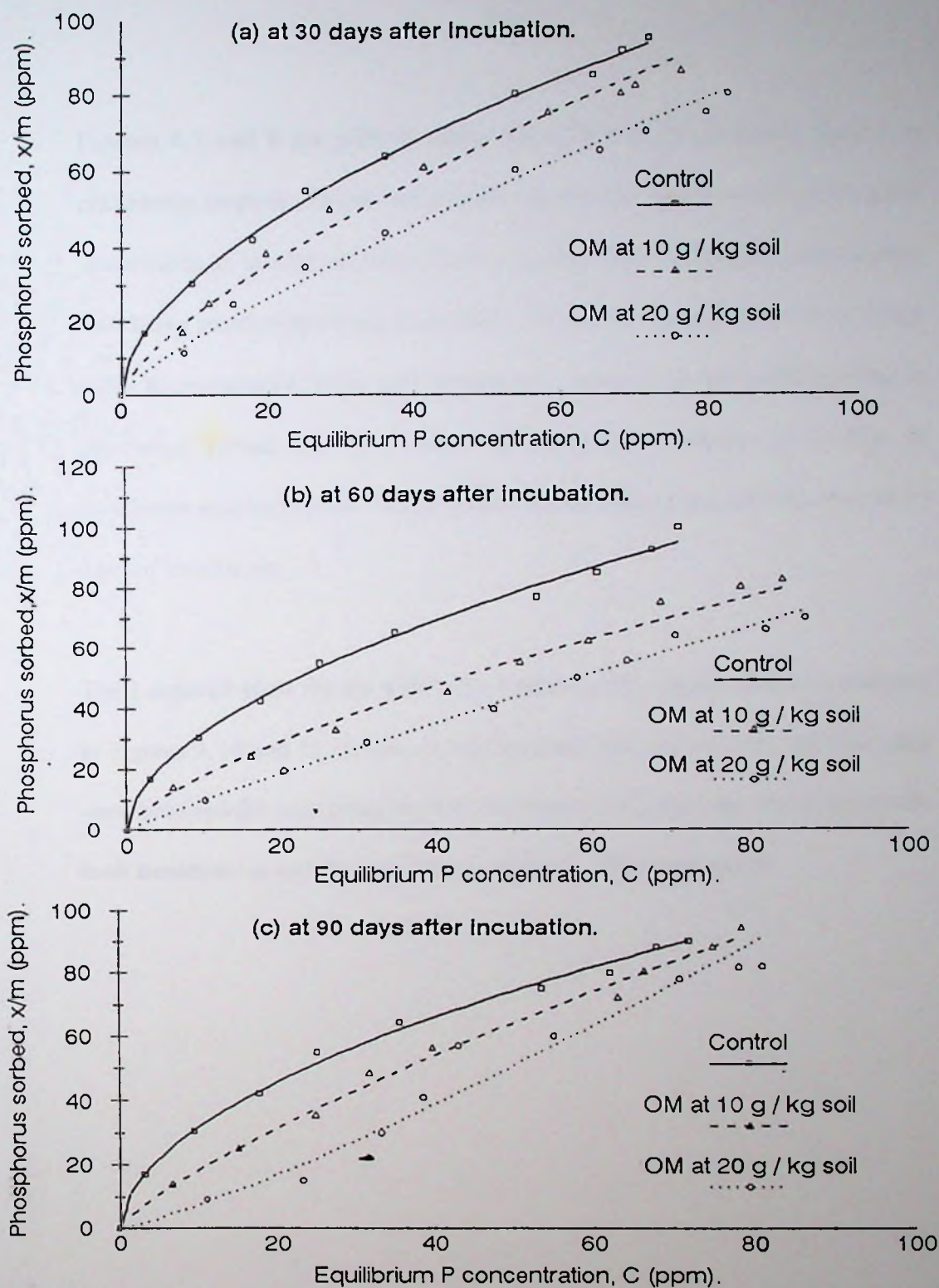


Fig. 5. Effects of organic matter application on phosphorus sorption isotherms of Sironko soil.

Figures 6,7 and 8 are plots to show the influence of incubation period on phosphorus sorption. In the control soils phosphorus sorption isotherms shifted upwnwards as incubation period increased, the shifts in Kamutur and Olweny soils being smaller than those in Sironko soil. For the organic matter treatments, in the Kamutur and Olweny soils phosphorus sorption increased with increase in incubation period; but for Sironko soil phosphorus sorption at 60 days of incubation was higher than that at 90 days of incubation but less than that at 30 days of incubation.

The Langmuir plots for the soils after organic matter application are presented in Figures 9, 10 and 11. In the soils of Kamutur and Olweny two straight lines were obtained for each treatment and for Sironko soil one line was obtained for each treatment as was the case before organic matter application.

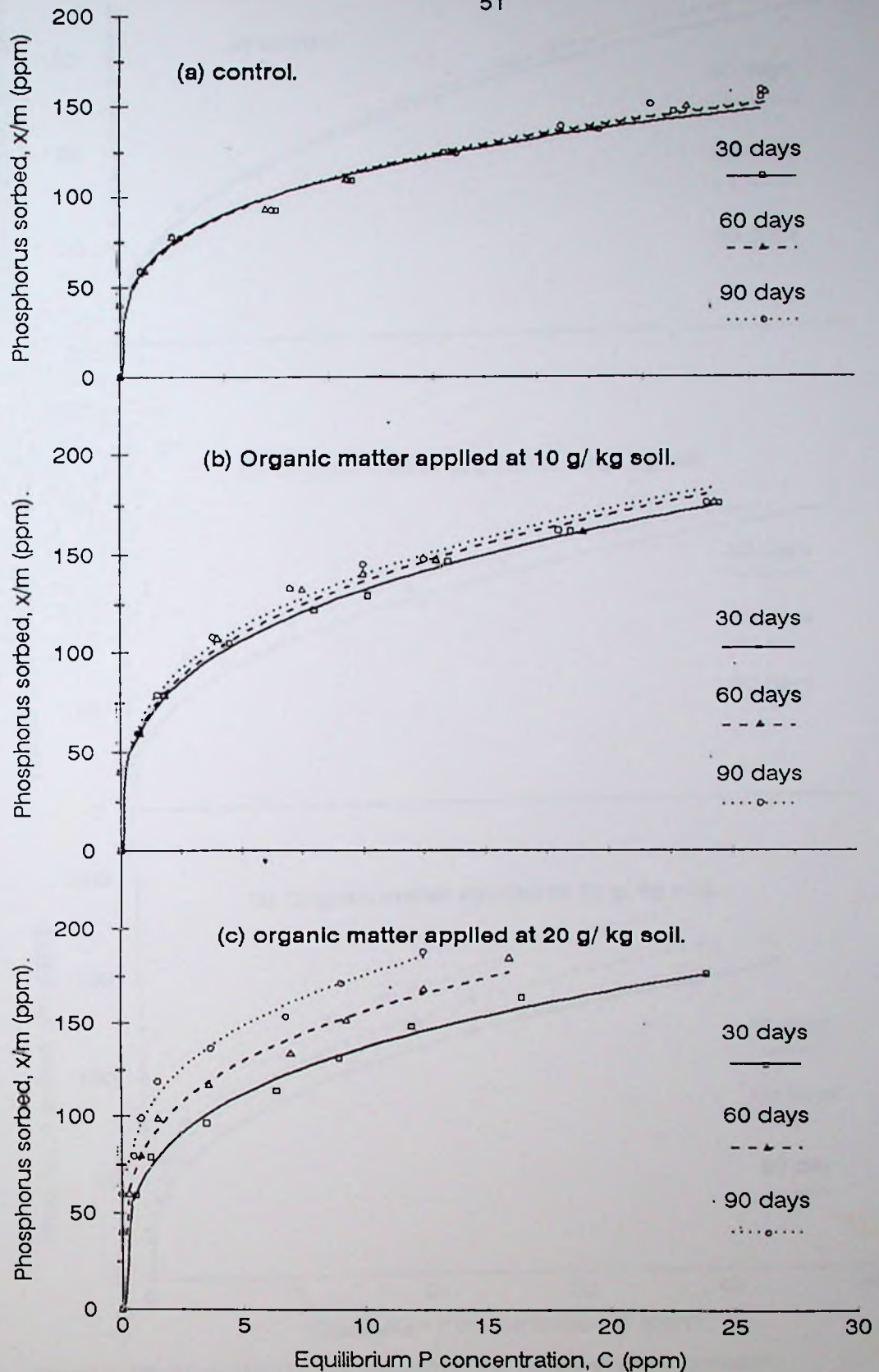


Figure 6. Influence of incubation period on the effects of organic matter application on phosphorus sorption isotherms of Kamutur soil.

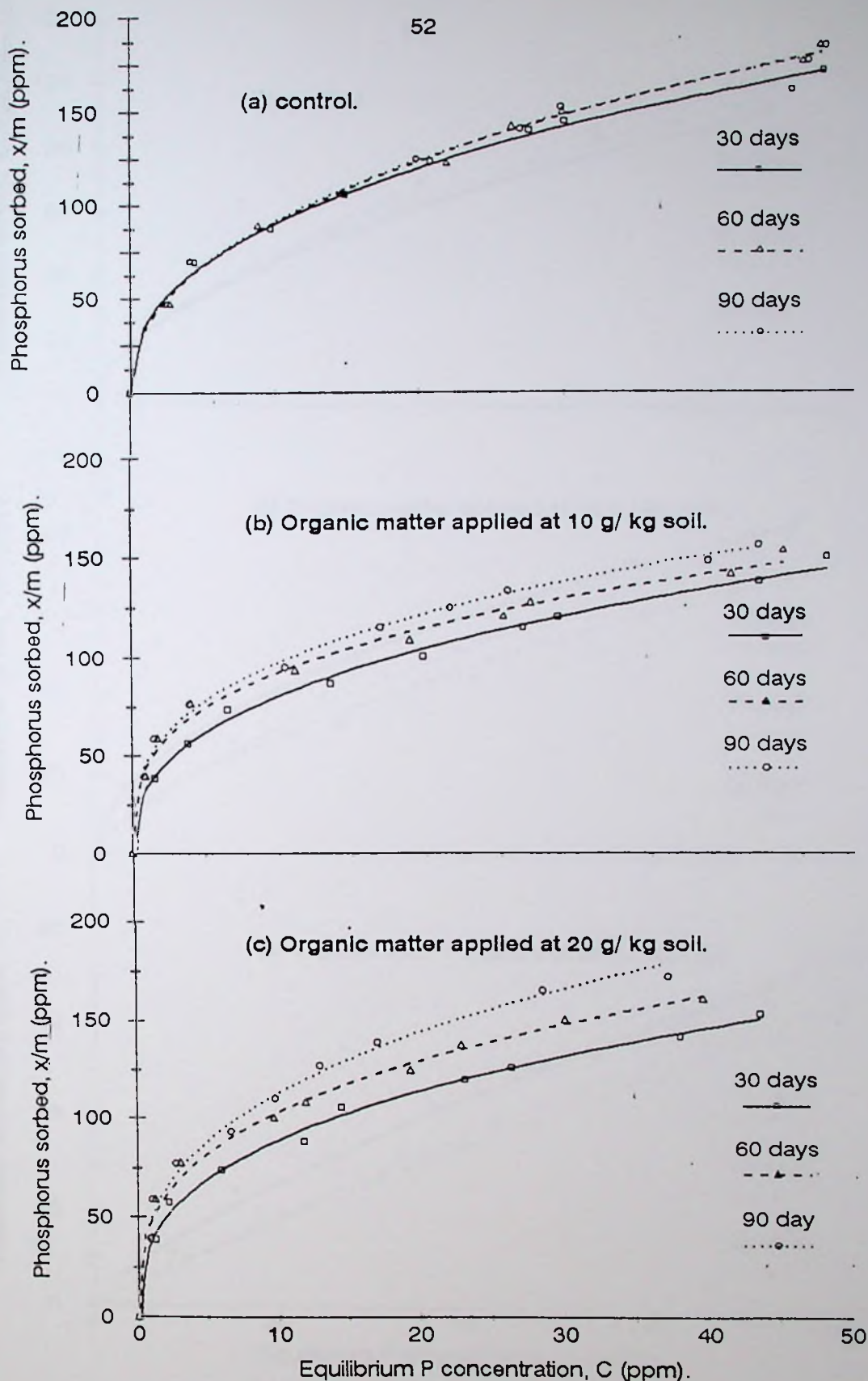


Figure 7. Influence of incubation period on the effects of organic matter application on phosphorus sorption isotherms of Olweny soil.

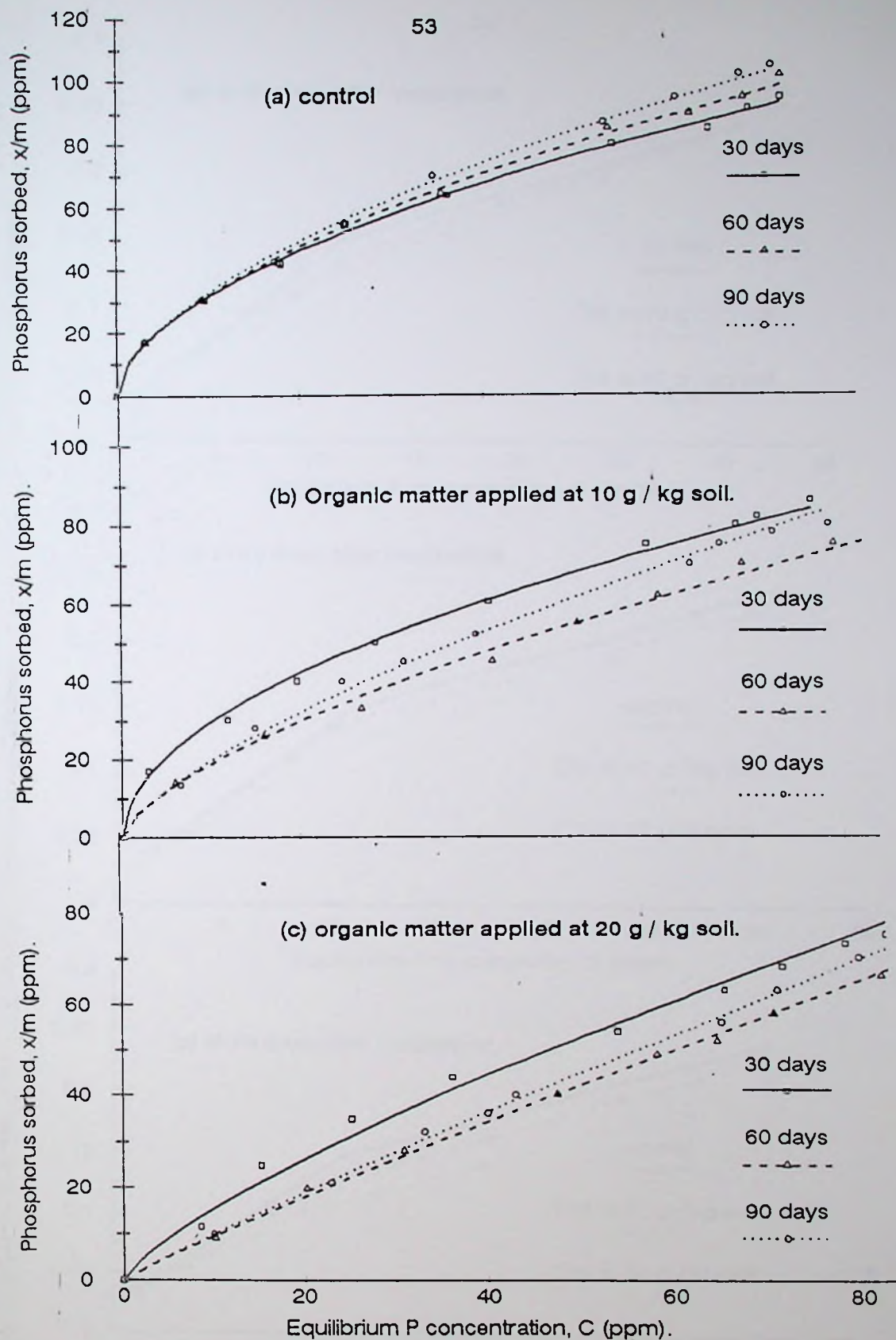


Figure 8. Influence of incubation period on the effects of organic matter application on phosphorus sorption isotherms of Sironko soil.

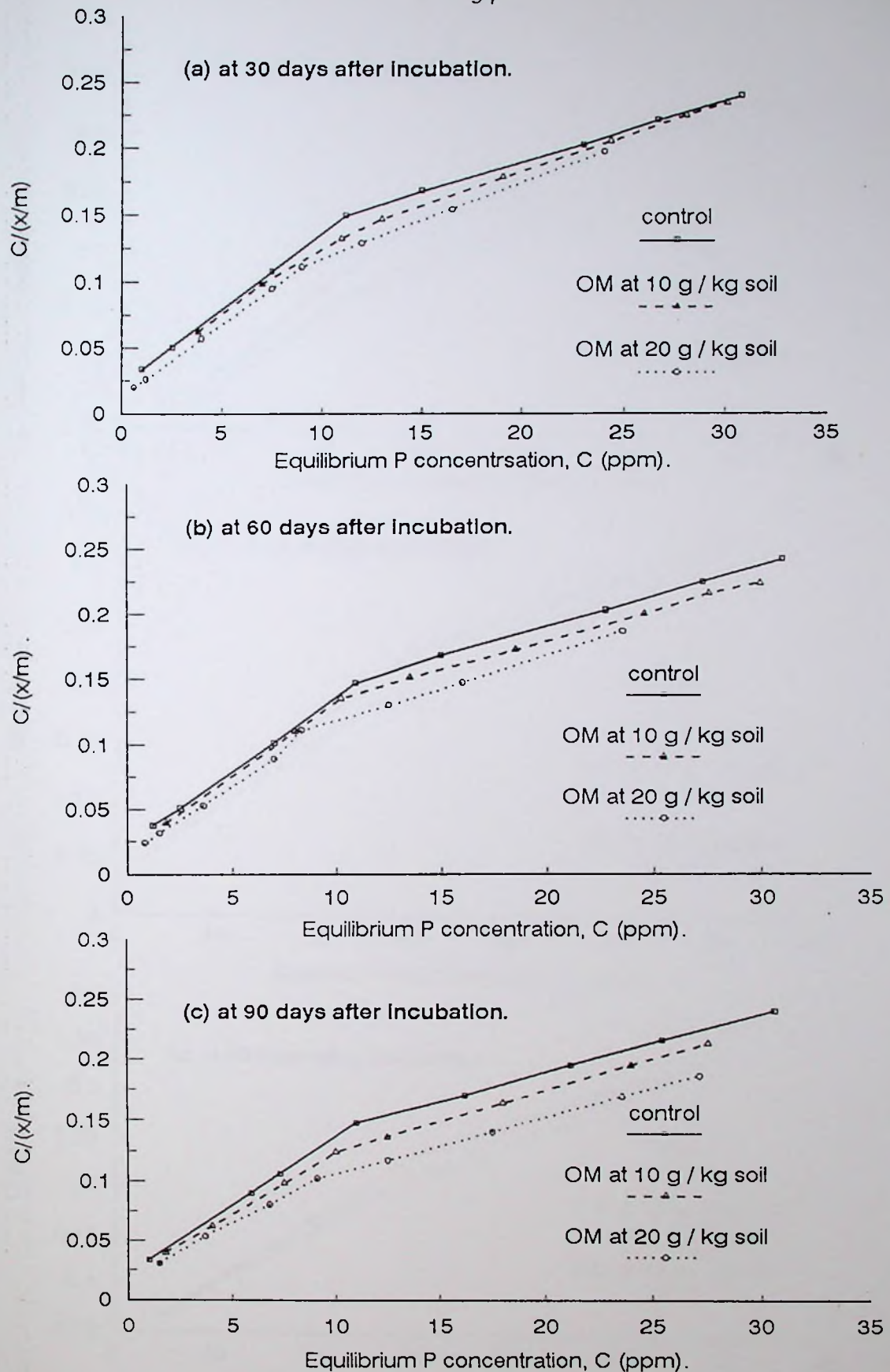


Fig. 9. Langmuir plots for P sorption in Kamutur soil after organic matter application.

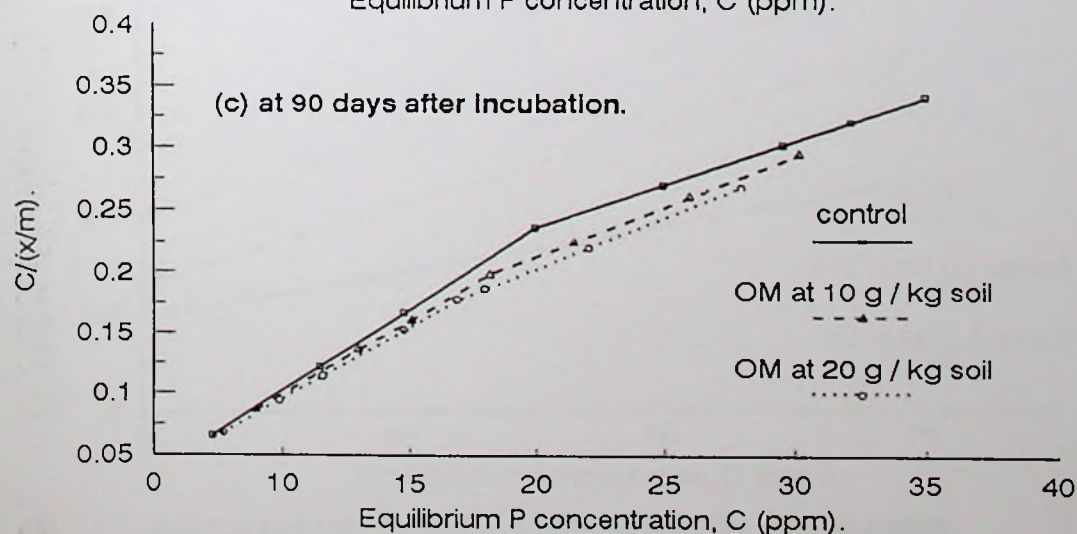
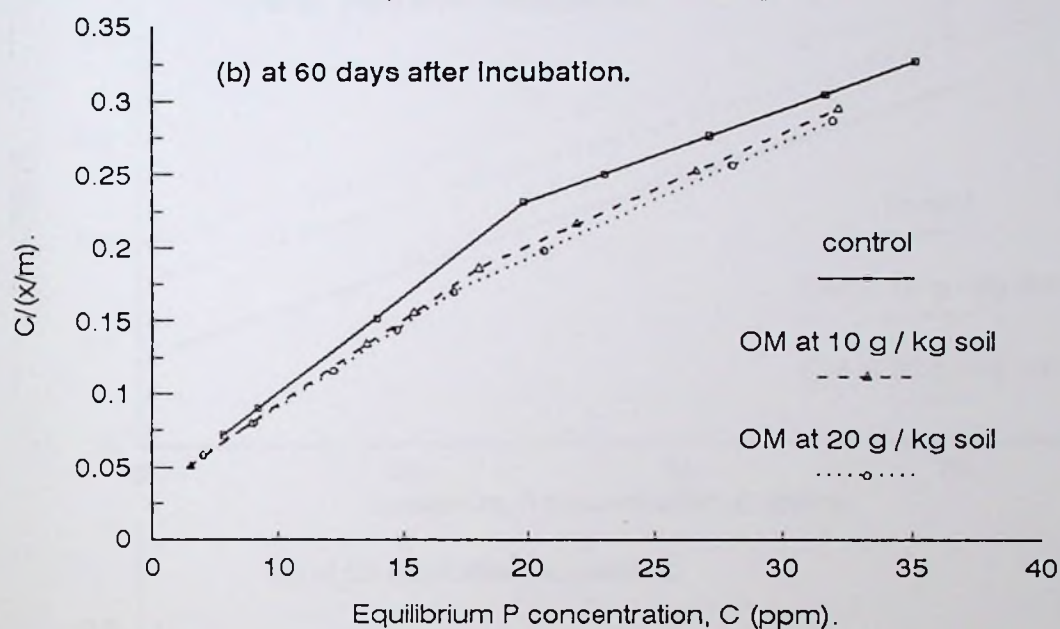
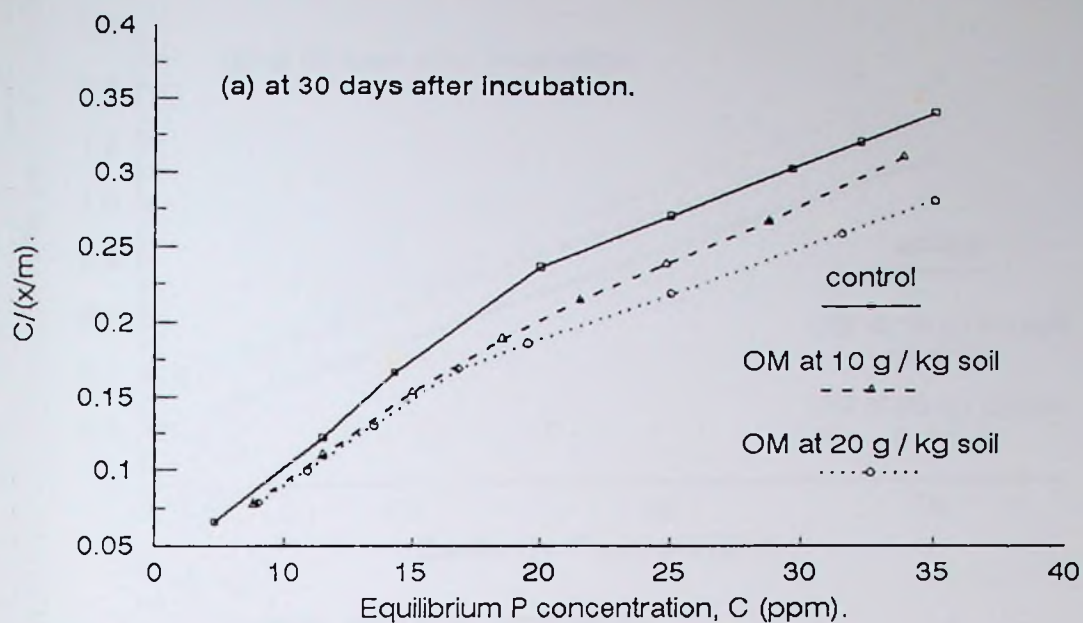


Fig. 10. Langmuir plots for P sorption in Olweny soil after organic matter application.

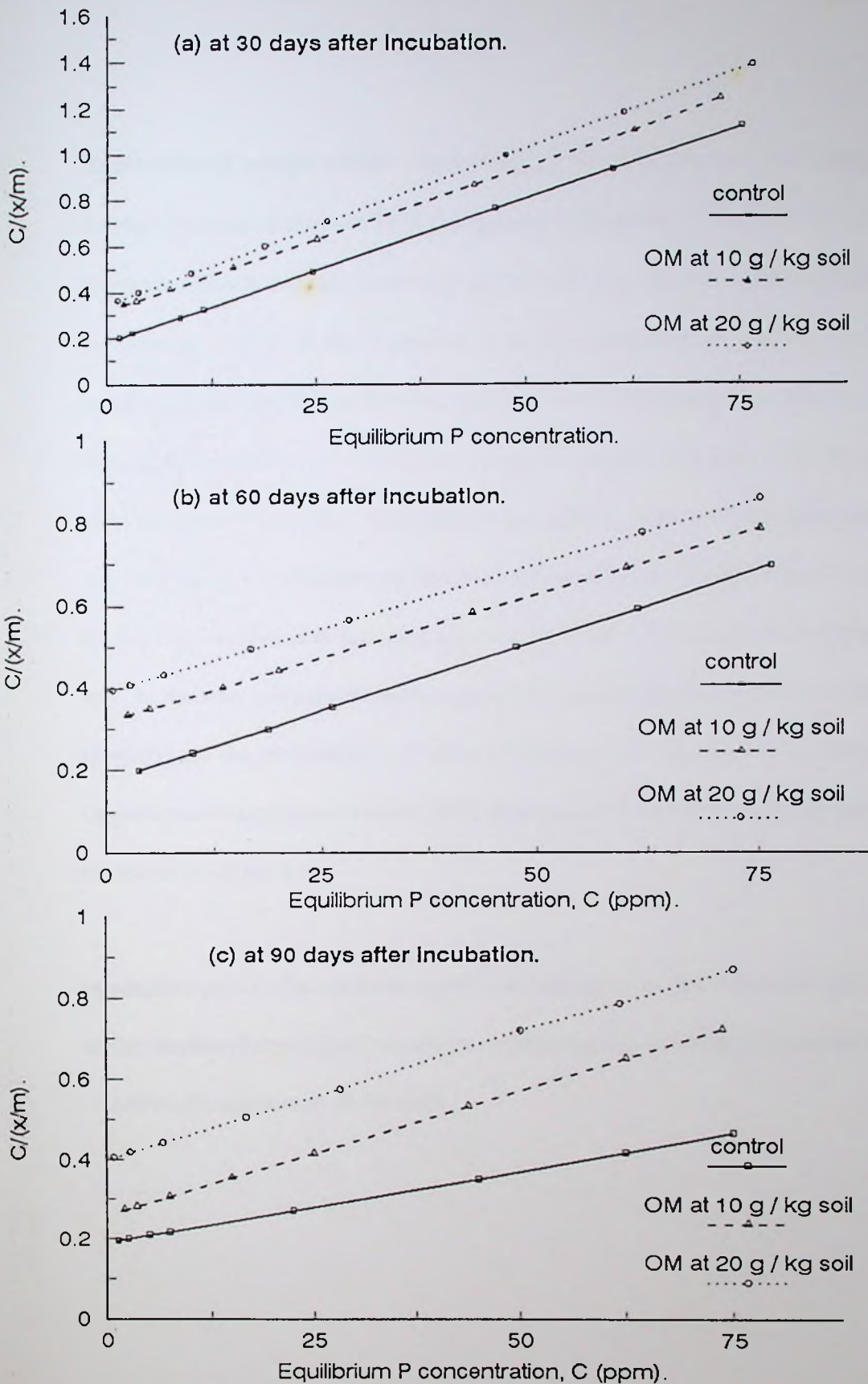


Fig. 11. Langmuir plots for P sorption in Sironko soil after organic matter application

Application of organic matter significantly ($p = 0.05$) increased the Langmuir sorption maxima of the soils from Kamutur and Olweny (Tables 5a and 5b); for Kamutur soil only organic matter application at 20 mg / kg soil caused significant increase ($p = 0.05$) in the Langmuir sorption maxima at 60 and 90 days of incubation. In the soil from Sironko, application of organic matter at 20g / kg soil significantly reduced ($p = 0.05$) the Langmuir sorption maxima at 60 days of incubation only (Table 5c). Compared to the control, organic matter application significantly ($p = 0.05$) depressed the availability of native phosphorus at 30 and 60 days of incubation in Kamutur soil, and at 30 days of incubation in Olweny soil. In Sironko soil organic matter application had a significant positive effect ($p=0.05$) on the availability of native phosphorus at 60 days of incubation. Organic matter application did not have significant effects on the bonding energy constants in all the soils.

Incubation period did not have significant influence on the effects of organic matter on phosphorus sorption maxima, bonding energy constants and availability of native phosphorus in all the soils.

Table 5a. Effects of organic matter application on the phosphorus sorption parameters and availability of native phosphorus in Kamutur soil.

(i) Langmuir sorption maxima (ppm P) for region I

Treatment	Incubation Period (days)		
	30	60	90
C	122.6	123.7	123.7
M ₁	124.4	126.0	126.5
M ₂	127.0	128.6	135.4
LSD _(0.05)	ns	4.2	4.8
C.V (%)	9.1	6.2	7.1

(ii) Langmuir sorption maxima (ppm P) for region II

Treatment	Incubation Period (days)		
	30	60	90
C	52.2	52.4	52.5
M ₁	52.6	53.1	53.3
M ₂	53.5	53.8	52.9
LSD _(0.05)	1.1	0.7	0.5
C.V (%)	11.7	7.5	5.5

(iii) Bonding energy constants for region I

Treatment	Incubation Period (days)		
	30	60	90
C	0.50	0.51	0.50
M ₁	0.48	0.45	0.45
M ₂	0.45	0.42	0.42
LSD _(0.05)	ns	ns	ns
C.V (%)	4.6	8.9	7.7

(iv) Bonding energy constants for region II

Treatment	Incubation Period (days)		
	30	60	90
C	0.10	0.11	0.11
M ₁	0.06	0.06	0.05
M ₂	0.05	0.03	0.03
LSD _(0.05)	ns	ns	ns
C.V (%)	7.3	6.7	8.6

(v) Bray I P (ppm)

Treatment	Incubation Period (days)		
	30	60	90
C	11.6	11.5	11.5
M ₁	7.8	8.5	10.5
M ₂	7.5	8.0	9.8
LSD _(0.05)	1.4	1.3	ns
C.V (%)	7.9	14.9	15.8

ns = not significant at $p = 0.05$.

Table 5b. Effects of organic matter application on the phosphorus sorption parameters and availability of native phosphorus in Olweny soil.

(i) Langmuir sorption maxima (ppm P) for region I

Treatment	Incubation Period (days)		
	30	60	90
C	108.4	109.2	109.8
M ₁	140.1	144.5	146.3
M ₂	142.0	147.0	150.0
LSD _(0.05)	4.8	8.8	9.0
C.V (%)	7.6	14.1	13.5

(ii) Langmuir sorption maxima (ppm P) for region II

Treatment	Incubation Period (days)		
	30	60	90
C	41.8	41.2	41.2
M ₁	46.8	47.5	48.4
M ₂	47.7	48.4	49.8
LSD _(0.05)	ns	1.4	1.5
C.V (%)	9.1	8.0	9.8

(iii) Bonding energy constants for region I

Treatment	Incubation Period (days)		
	30	60	90
C	0.37	0.38	0.37
M ₁	0.35	0.33	0.32
M ₂	0.34	0.32	0.32
LSD _(0.05)	ns	ns	ns
C.V (%)	17.7	14.6	17.4

(iv) Bonding energy constants for region II

Treatment	Incubation Period (days)		
	30	60	90
C	0.03	0.03	0.02
M ₁	0.03	0.02	0.02
M ₂	0.03	0.02	0.01
LSD _(0.05)	ns	ns	ns
C.V (%)	15.5	16.7	14.6

(v) Bray I P (ppm)

Treatment	Incubation Period (days)		
	30	60	90
C	6.6	6.7	6.6
M ₁	4.7	6.2	6.3
M ₂	4.5	5.7	6.2
LSD _(0.05)	1.3	ns	ns
C.V (%)	11.4	6.1	8.9

ns = not significant at $p = 0.05$.

Table 5c. Effects of organic matter application on the phosphorus sorption parameters and availability of native phosphorus in Sironko soil.

(i) Langmuir sorption maxima (ppm P)

Treatment	Incubation Period (days)		
	30	60	90
C	98.2	98.2	98.6
M ₁	97.5	96.1	96.1
M ₂	96.1	94.4	95.2
LSD _(0.05)	ns	6.1	ns
C.V (%)	5.7	6.1	12.5

(ii) Bonding energy constants

Treatment	Incubation Period (days)		
	30	60	90
C	0.08	0.07	0.07
M ₁	0.06	0.04	0.03
M ₂	0.05	0.03	0.03
LSD _(0.05)	ns	ns	ns
C.V (%)	6.3	4.1	14.6

(iii) Bray I P (ppm)

Treatment	Incubation Period (days)		
	30	60	90
C	39.2	39.2	39.0
M ₁	38.6	36.8	37.2
M ₂	38.5	32.3	36.4
LSD _(0.05)	ns	4.7	ns
C.V (%)	10.7	12.9	14.1

ns = not significant at $p = 0.05$

4.4 Fractionation of inorganic phosphorus

The total phosphorus and inorganic phosphorus fractions are presented in Table 6. The highest total phosphorus value was in the soil from Kamutur (1322 ppm) and the lowest in the soil from Olweny (335 ppm). The relative abundance of the inorganic phosphorus fractions was in the order Red-P > Al-P > Ca-P > Fe-P in the soils from Kamutur and Olweny; Ca-P and Fe-P reversed positions for the Sironko soil.

4.5 Effects of phosphorus application on the inorganic phosphorus fractions in the soils

For Kamutur and Olweny soils active inorganic phosphorus fractions increased with phosphorus application rates (Figures 12 and 13). In Kamutur soil there was significant treatment effect ($p = 0.05$) on Al-P at the incubation period of 90 days, and only with the 30 mg P kg⁻¹ soil treatment (Figure 12). There were significant treatment effects ($p = 0.05$) on Ca-P at 30 and 60 days of incubation but at 90 days the treatment effects had become insignificant. For Fe-P, significant treatment effects ($p = 0.05$) were observed at 60 and 90 days of incubation and only for the 30 mg P kg⁻¹ treatment. Phosphorus application had no significant effect on Red-P.

Table 6. Total P and inorganic P fractions values (ppm) of the soils.

Soil	Total P	Inorganic P fractions			
		Al-P	Fe-P	Ca-P	Red-P
Kamutur	1322	36.1 (2.7)	4.3 (0.3)	17.6 (1.3)	177.3 (8.9)
Olweny	335	38.3 (11.4)	1.8 (0.5)	2.6 (0.8)	123.1 (36.7)
Sironko	374	62.9 (16.8)	22.6 (6.0)	10.1 (2.7)	177.3 (47.4)

Values in brackets are inorganic phosphorus fractions expressed as percent of total P contents of the soils.

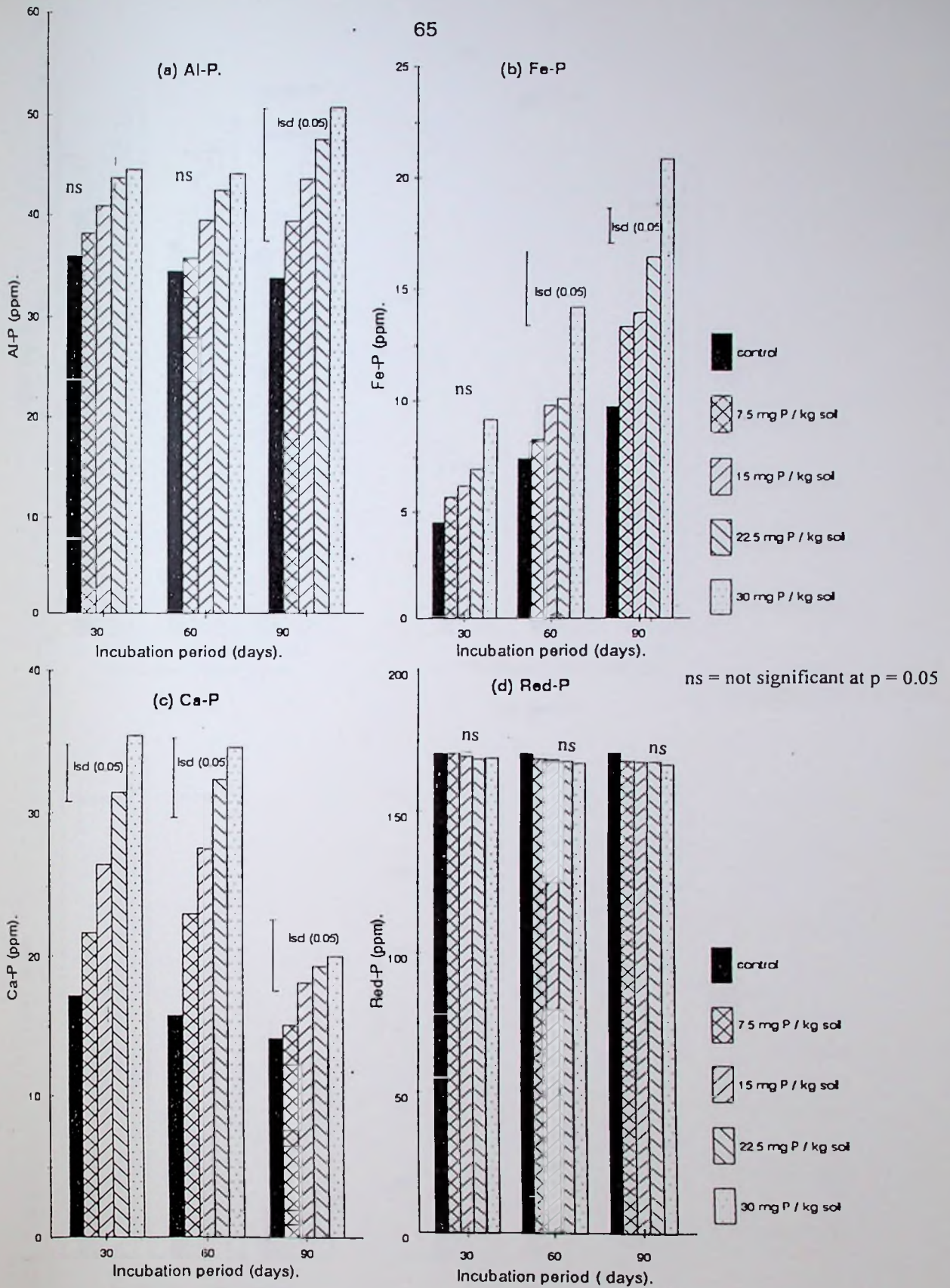


Figure 12. Effects of phosphorus application on the inorganic phosphorus fractions of Kamutur soil.

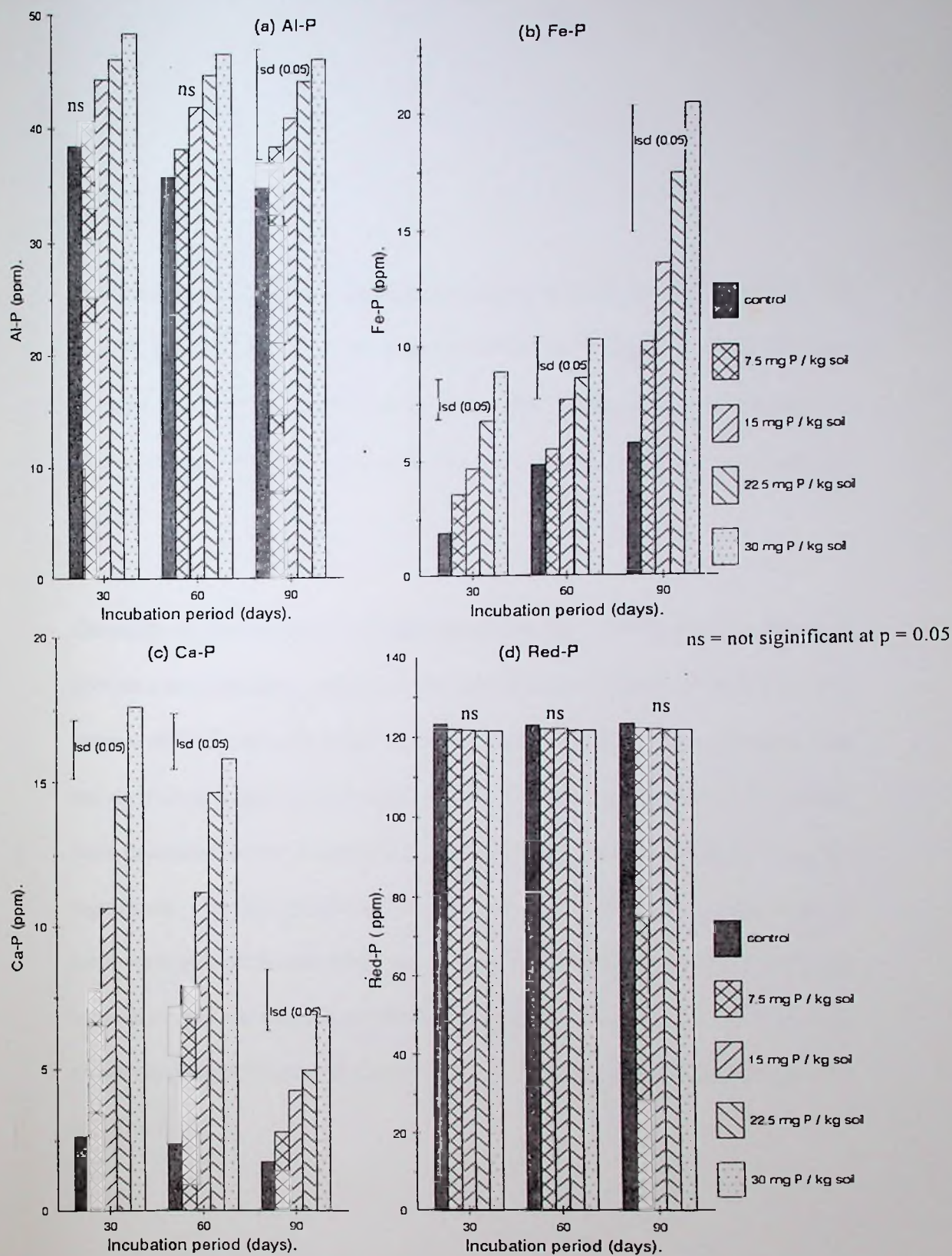


Figure 13. Effects of phosphorus application on the inorganic phosphorus fractions of Olweny soil.

In the soil from Olweny, phosphorus application also had no significant effect on Red-P. For Ca-P and Fe-P the treatment effects were significant ($p = 0.05$) but not all treatments were significant throughout the incubation periods (Figure 13). The treatment effects on Al-P were not significant throughout the incubation period.

Generally incubation period had significant influence ($p=0.05$) on the effects of phosphorus application on Fe-P and Ca-P fractions (Figures 14 and 15). The amount of Fe-P increased as the incubation period increased but the increase was not significant in the control for Olweny soil. The amount of Ca-P in the control soils decreased as the incubation period increased but the decreases were not significant. In the phosphorus treated soils Ca-P increased at 60 days of incubation then decreased at 90 days. Compared to the Ca-P data at 30 days, the increases were not significant but the decreases were ($p = 0.05$). In both soils incubation period did not influence the effects of phosphorus application on Al-P and Red-P.

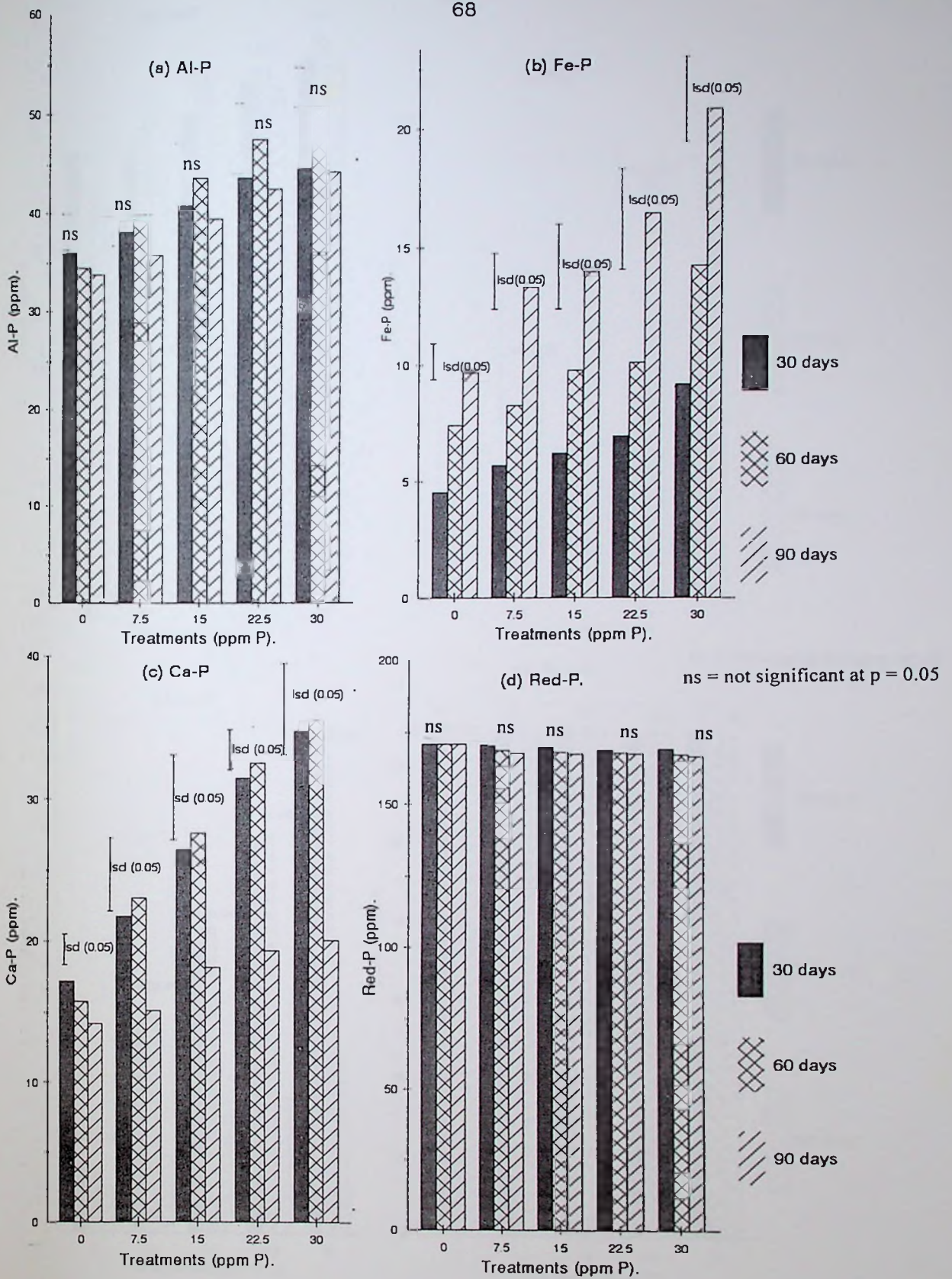


Figure 14. Influence of incubation period on the effects of P application on inorganic P fractions in Kamutur soil.

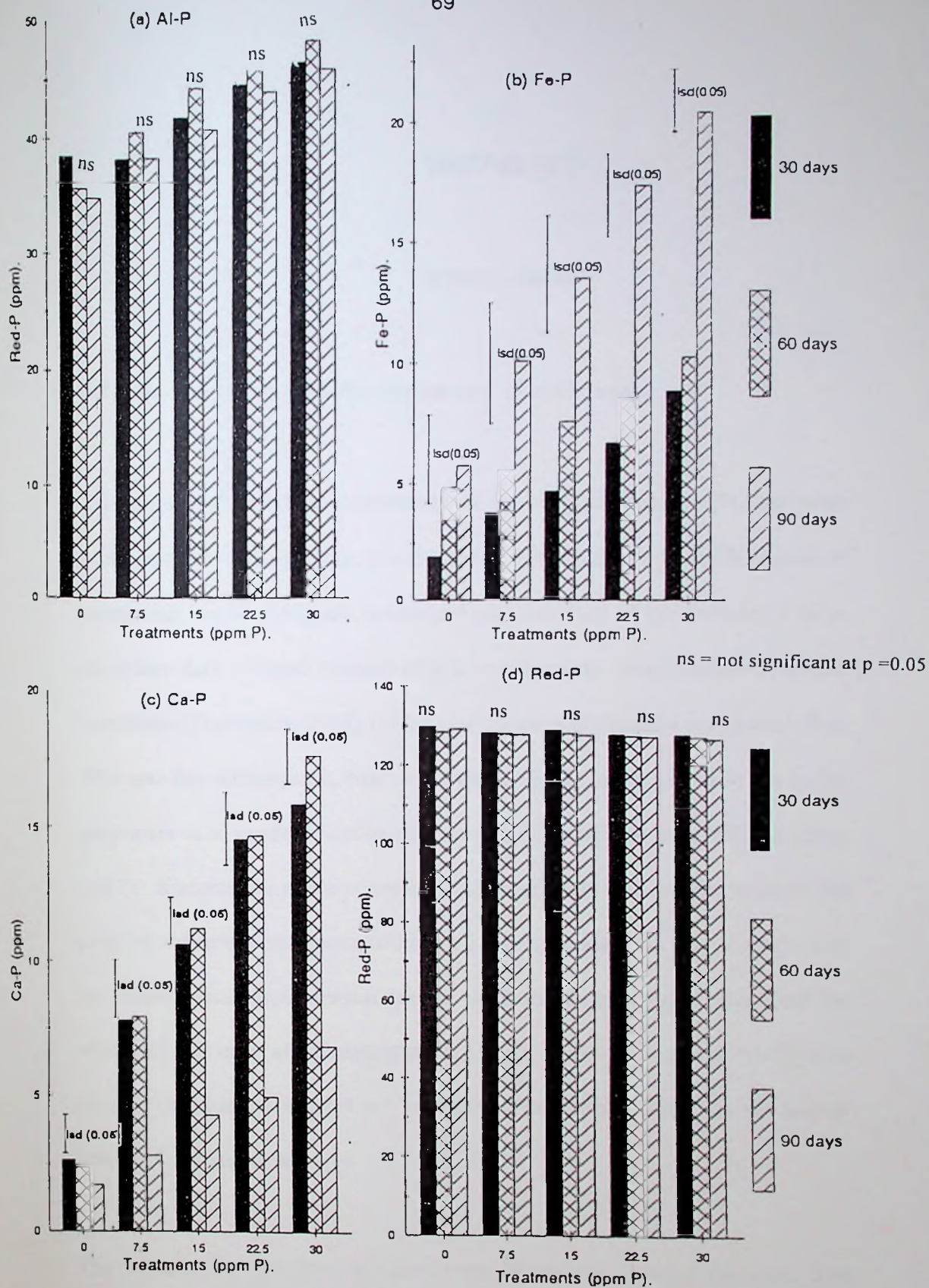


Figure 15. Influence of incubation period on the effects of P application on inorganic P fractions in Olweny soil.

CHAPTER FIVE

DISCUSSION

5.1 Site, profile and soil description and identification

The soils under study are confirmed to be Vertisols because (i) they were predominantly dark in colour, which Singh (1956) attributed to the formation of complexes between organic matter and clay fractions of the soils and / or to secondary dark coloured minerals of iron or manganese formed under anaerobic conditions (FitzPatrick, 1983), (ii) the clay contents in the soils was greater than 30% and the exchangeable base status was high . These are some of the major properties used in identification of Vertisols (Coughlan et al, 1987; Le Mare, 1987). Smooth shiny faces were also observed in the sub-surface soils of the profiles, reflecting movement within the soil mass during the rainy season. The movement results from uneven wetting which causes swelling pressure and the sliding of soil mass along each other (Blokhuys, 1989). Jewitt et al (1979) also pointed out that the internal soil movements in Vertisols generate the glossy nature of ped surfaces.

The colour of the soils show that there were differences between the soils. The lower chroma of the profiles in Kamutur and Olweny reflect the less favourable

drainage conditions in the soil due to the high clay content of clay in the soils and the topographic positions of the soils which are in low lying areas. The high chroma of the surface soil in Sironko soil is indicative of better drainage in the surface of the soil profile.

The levels of available phosphorus in Kamutur and Olweny soil are below 20 ppm P but that of Sironko soil is higher than this value considered by Jackson (1958) to be adequate. This implies that, currently, Sironko soil has adequate available phosphorus and does not need phosphorus application but the soils from Olweny and Kamutur may need phosphorus application for higher crop production. In Ethiopian Vertisols Desta Beyene (1988) indicated that application of phosphorus at the rates of 13-40 kg P ha⁻¹ was adequate for crops such as barley, wheat, teff, oilseeds and pulses. For the soils of Kamutur and Olweny the current recommended rates for the crop to be grown could be used; however the correct rates need to be determined from field trials.

The high content of exchangeable sodium suggests that the soils have poor physical properties due to the dispersing effect of sodium in soils. Exchangeable sodium enhances swelling and cracking of Vertisols (Le Mare 1987).

5.2 Sorption Characteristics

The trend of phosphorus sorption in the soils appears related to the contents of exchangeable calcium in the soils. Kamutur soil which had the highest content of exchangeable calcium sorbed the highest amount of phosphorus, and Sironko soil which had the lowest content of exchangeable calcium sorbed the least amount of phosphorus.

Phosphorus sorption data can be described by one or more Langmuir relationships depending on the difference in the energy of adsorption at highly reactive and less reactive sites (Rajan and Fox, 1975). Phosphorus sorption in Kamutur and Olweny soils deviated from the single line Langmuir relationship, suggesting that there could have been creation of new sites at high concentrations of phosphorus due displacement of structural silicates similar to those reported by Rajan and Fox (1975) for acidic oxidic soils. Exchangeable calcium in Kamutur and Olweny soils could have caused precipitation of phosphorus and contributed to the observed deviations. Taylor and Ellis (1978) attributed deviation of phosphorus sorption in Typic and Aquallic Hapludalfs to precipitation of phosphate ions by calcium. Phosphorus sorption by calcium carbonate deviated from the single line Langmuir relationship and this was attributed to precipitation of phosphate (Kuo and Lotse, 1972).

Ryden et al (1977) explained the observed deviation of phosphorus sorption data for soils and hydrous ferric oxide gel from the single line Langmuir relationship to be due to two different types of reaction mechanisms in the phosphorus sorption process. However, Syers et al (1973) attributed the deviation of phosphorus sorption from the single line Langmuir relationship in soils (vertic Agriudoll, Agriudoll and Haplohumox) to the existence of two population sites which have a widely differing affinity for phosphorus.

Phosphorus sorption in Sironko soil conformed to the single line Langmuir relationship, suggesting that sorbed phosphate formed a monolayer on the sorbent surfaces.

Basing on the classification of soils in terms of phosphorus sorption by Sanchez and Uehara (1980) the Vertisols used in this study are very low to low phosphorus fixing soils. Sanchez and Uehara (1980) considered soils that sorb 150 ppm P or more at equilibrium phosphorus concentration of 0.2 ppm P to be high phosphorus fixing soils. The standard phosphorus requirements (SPR) for the soils are lower than those of Ethiopian Vertisols where Tekalign Mamo et al (1988) found SPR ranging from 87-600 ppm P. The soils used in this study sorbed less phosphorus apparently due to the low levels of amorphous oxides of iron and aluminum.

5.3. Effects of organic matter application on phosphorus sorption and availability of native phosphorus in the soils

Organic matter application increased phosphorus sorption maxima of Kamutur and Olweny soils but reduced the bonding energy constants. Increase in phosphorus sorption due to organic matter application has been reported by other workers (Harter, 1969; Hinga, 1973; Singh and Jones, 1976; Wada and Gunjigake, 1979). Reasons given for the increase include: (i) inhibition of crystallisation of aluminum and iron oxides (i.e. conversion of amorphous oxides to crystalline forms) by organic matter (Borggaard, 1983), (ii) anion exchange reaction between soil organic matter and added phosphate (Harter, 1969), (iii) release of aluminum and iron ions by the decomposition of organic matter which participate in phosphorus sorption (Gikonyo et al 1994). Sah and Mikkelsen (1989) also observed increase in phosphorus sorption due to addition of organic matter in soil under flooded-drained conditions; apparently due to increases in amorphous iron oxides (Sah et al, 1989). For this study, a better explanation appears to be that advanced by Singh and Jones (1976) that addition of organic residues with phosphorus content of less than 0.3% P in soil which has low level of available phosphorus increases phosphorus sorption in the soil due to microbial immobilisation of phosphorus in the soil which reduces labile phosphorus. In this study the organic materials used did not have detectable amounts of phosphorus,

and immobilisation of phosphorus was also reflected in the reduction in the level of available phosphorus (Bray I P) in the soils treated with organic matter (Tables 5a and 5b).

In the soil from Sironko organic matter application reduced the Langmuir sorption maxima and the bonding energy constant. Zhang et al (1993) also found that incubation of soils (Entisol and Ultisol) from China with cellulose reduced adsorption of phosphorus in the soils. Decrease in phosphorus sorption after organic matter application has been observed by Earl et al (1979), Meek et al (1979) and Sibanda and Young (1986). The reasons for this include: (i) organic anions forming soluble complexes with iron and aluminum from soil components thereby eliminating a portion of phosphorus sorbing sites in the soil (Earl et al, 1979); and (ii) competitive specific sorption of organic anions where there is competition between phosphate and organic anions, the organic anions blocking potential sorbing sites on the inorganic soil particles (Appelt et al, 1975a; Earl et al, 1979 and Parfitt, 1977). The reduction in phosphorus sorption in Sironko soil after organic matter application suggests that organic matter decomposition resulted in the production of organic anions that were able to block some of the potential sites for phosphorus sorption through competitive specific anion sorption resulting in the observed reduction in phosphorus sorption. Specific sorption of anions increases the negative charge on the surface of the sorbent

(Barrow, 1978); and Appelt et al (1975a) found that specifically sorbed organic anions reduced phosphorus sorption. The specific sorption of organic anions from the decomposition of organic matter could have created greater electrostatic repulsion of phosphate ions so reducing phosphorus sorption. This is supported by the reduction in the bonding energy constants after organic matter application in Sironko soil (Table 5c).

However, the effect of organic matter in reducing phosphorus sorption in the soil seems to be transient because phosphorus sorption in the soil samples treated with organic matter was lower at 60 days of incubation than at 30 days of incubation and then higher at 90 days of incubation than at 60 days of incubation (Table 5c and Fig 8); implying that more sites were becoming available for phosphorus sorption. This is supported by the observation by Afif et al (1995) that the effect of organic matter in blocking phosphorus sorption sites in soils is temporary.

The decrease in bonding energy constants due to organic matter application in the soils from Kamutur and Olweny Rice Scheme could be due to increase in the amount of phosphate sorbed which reduced the positive charge density on the sorbents, so reducing the force of attraction for the phosphate ions onto the soil constituents involved in phosphate sorption.

The reasons for the opposing effects of organic matter on phosphorus sorption in Kamutur and Olweny soils versus Sironko soil are not clear. However, it could be due to the differences in the levels of available phosphorus in the soils relative to the phosphorus content of the organic material added in the soils. Addition of organic matter induced immobilisation of phosphorus in all the 3 soils (Tables 5a, 5b and 5c); but in Sironko the level of available phosphorus was still high, so immobilisation could not increase phosphorus sorption in this soil.

5.4 Fractionation of inorganic phosphorus

The total phosphorus contents appear to have been influenced by the parent materials. The soil from Olweny, derived from alluvial deposits (Ollier, 1959), had the lowest amount of total phosphorus and the soil from Kamutur, derived from mixed volcanic-metamorphic rocks (Ollier and Harrop, 1959), had the highest value of total phosphorus.

The contents of Al-P and Fe-P in the soils are related to the contents of oxalate extractable oxides of aluminum and iron respectively. Sironko soil which had the highest content of oxalate extractable aluminum oxides also had the highest content of Al-P and Kamutur soil which had the lowest content of oxalate extractable aluminum oxides also had the lowest content of Al-P. Similarly,

Sironko soil had the highest content of oxalate extractable oxides and Fe-P, and Olweny soil had the lowest contents of oxalate extractable iron oxides and Fe-P.

Aluminum bound phosphorus (Al-P) was the predominant active inorganic phosphorus fraction in the soils possibly because of the higher contents of aluminum oxides than iron oxides in the soils (Table 3) which implies that more phosphorus was sorbed by aluminum oxides than iron oxides. In Ethiopian Vertisols, Tekalign Mamo et al (1988) found that Fe-P was the predominant active inorganic phosphorus fraction, followed by Ca-P and then Al-P. The contents of oxalate extractable oxides of aluminum and iron in the Ethiopian Vertisols were not indicated but the contents of CDB extractable oxides of aluminum and iron ranged from 0.02-0.53 % and 0.29-3.88% respectively.

Of the inorganic phosphorus fractions determined Red-P had the highest value in all the soils, ranging from 123 to 177.3 ppm (Table 6). The values are higher than those reported by Solis and Torrent (1989b) for calcareous Vertisols of Spain which ranged from 11.7-50.4 ppm P. The high content of Red-P in these soil is due to the seasonal flooding in these soils which causes redox fluctuations in the soils. This causes development of iron oxide coatings resulting in formation of Red-P. McKenzie et al (1977) indicated that reductant soluble phosphorus (Red-P) and Fe-P are of limited usefulness for the growth of upland crops.

5.5 Effects of phosphorus application on inorganic phosphorus fractions in the soils

In both Kamutur and Olweny soils most of the added inorganic phosphorus was recovered as Ca-P followed by Al-P at 30 and 60 days of incubation. This is due to the high level of exchangeable calcium in the soils, so most of the applied inorganic phosphorus was initially fixed as calcium phosphate. At 90 days of incubation most of the added phosphorus was recovered as Al-P, showing a shift from the more soluble Ca-P to the less soluble Al-P.

Some of the observed changes in the inorganic phosphorus fractions can be explained in terms of the reaction of the superphosphate fertilizer in the soils. The granules of superphosphate are known to absorb water in the soil and the solution that diffuses from the granules has low pH and is very reactive (Sample et al, 1980; Wild, 1988). This causes dissolution of some of the soil constituents, placing relatively large amounts of reactive cation, especially iron and aluminum, in solution and these participate in phosphorus retention reactions. The observed decrease in Red-P and the initial increase in Fe-P and Al-P could be due to dissolution of iron and aluminum oxide coatings of Red-P so reducing the amount of Red-P, and iron and aluminum oxides released from the coatings reacted with

phosphate anions so increased the Fe-P and Al-P levels.

The initial increase in Al-P was greater than the increase in Fe-P in samples that received phosphorus fertilizer. This can be attributed to the greater reactivity of amorphous (oxalate extractable) aluminum oxides than amorphous iron oxides; and the higher content of amorphous aluminum oxides than amorphous iron oxides in the soils (Hsu, 1964). In the samples that received phosphorus fertilizer Al-P decreased after 60 days of incubation but Fe-P increased throughout incubation. This is related to the solubility of the two compounds; Al-P is more soluble than Fe-P so, as pointed out by Shelton and Coleman (1968), with time Al-P is solubilised and refixed as Fe-P. The decrease in Ca-P and Al-P in the control and in the phosphorus treated samples between 60 and 90 days of incubation indicates a shifting of phosphorus from these fractions, which are more soluble, to the less soluble Fe-P. This is reflected in the increase in Fe-P. Tu et al (1993) also found that in a calcareous Fluvisol superphosphate was transformed largely to the less soluble and less available Fe-P.

CHAPTER SIX

CONCLUSIONS AND RECOMMENDATIONS

Studies were conducted to determine the phosphorus status and sorption characteristics in three Vertisols of Uganda. There were quantitative differences in the status of native phosphorus in the soils. Total phosphorus was highest (1322 ppm P) in Kamutur soil, followed by Sironko soil (374 ppm P) and lowest (335 ppm P) in Olweny soil. In all the soils the reductant-soluble phosphorus was the highest inorganic phosphorus fraction attributed to the seasonal flooding which favours the development of iron oxide coatings that form reductant-soluble phosphorus. However, of the active (non-occluded) inorganic phosphorus fractions (Al-P, Ca-P and Fe-P) aluminum-bonded phosphorus (Al-P) was predominant in all the soils. The levels of available phosphorus determined by the Bray I method were low in the Kamutur and Olweny soils, and high in Sironko

On the basis of the results of this study, no immediate phosphate fertilization is recommended for Sironko soil because of the high level of available phosphorus; however, the soils of Kamutur and Olweny need phosphate fertilization for higher crop yields. From the standard phosphorus requirements determined from the sorption isotherms, up to 92.22 kg P ha⁻¹ and 72.16 kg P ha⁻¹ would be required for maximum crop growth in Kamutur and Olweny soils. These rates are high

and may not be economic, so there is need to determine the correct economic rates for the soils from field experiments.

Results from incubation studies showed that most the added inorganic phosphorus was recovered as Ca-P at 30 and 60 days of incubation. So most of the phosphorus applied would be available to crops in the short term since the availability of Ca-P is greater than those of Al-P and Fe-P. As the incubation period increased to 90 days most of the added phosphorus was recovered as Al-P followed by Fe-P, showing a shift from the more soluble Ca-P to the less soluble Al-P and Fe-P.

The bonding energy constants for the soils were low, indicating that phosphorus is weakly held in the soils and can easily be available to plants.

Organic matter application had different effects on phosphorus sorption in the soils. Application of organic matter increased phosphorus sorption in Kamutur and Olweny soils but reduced it in Sironko soil. The implications of adding organic matter to soil on phosphorus fertilization are that phosphorus fertilizer rates estimated from sorption isotherms before addition of organic matter may need to be modified following addition organic matter. This is because organic matter application may increase or decrease the phosphorus requirement of the

soil. Secondly, the period of time following the application of organic matter should be taken into consideration because the reduction in phosphorus sorption after organic matter application appears to be transient.

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