A COMPARATIVE STUDY OF THE PHOSPHORUS CHARACTERISTICS OF OIL PALM VOLCANIC SOILS IN PAPUA NEW GUINEA AND NEW ZEALAND VOLCANIC SOILS

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ABSTRACT

Oil Palm (*Elaeis guineensis* Jacq.) grown on volcanic ash soils in Papua New Guinea (PNG) generally respond well to N fertilisers but shows a lack of consistent response to inorganic phosphorus (P) fertilisers. This is true even on soils with high phosphate retention (PR) and where Olsen P values highlighted in the preliminary survey of PNGOPRA field trial data are very low (<10 mg/kg). A notable exception occurs at Bialla (Trial 201) where significant responses (yield and growth parameters) to P fertilisers have been found on soils with very low Olsen P (< 4 mg/kg) and very high PR values (>90% to at least 60 cm depth).

This study was done to characterise the PNG oil palm growing volcanic soils in relation to P responsiveness, to identify P fractions and their relative amounts, to determine the fate of applied P fertilisers and to compare chemical and mineralogical characteristics of PNG soils with some New Zealand (NZ) equivalent soils.

Mineralogical analysis indicates that the PNG soils used in this study are relatively young as evidenced by the presence of very high amounts of readily-weatherable volcanic glass in the sand, silt and clay fractions. Soils at Hoskins, Kapiura and Bialla, all in West New Britain (WNB) Province, contain similar amounts and types of primary and secondary minerals. Soils at Bialla are probably older than those at Hoskins and Kapiura and contain large amounts of secondary amorphous minerals (allophane and ferrihydrite) in the clay fraction. Soils at Popondetta are different from those in WNB with high amounts of hornblende and no augite or hypersthene in the heavy mineral fraction. Allophane levels in the clay fraction are high to very high in soil surface layers at Hoskins and Kapiura and at all depths in Bialla soils. At Popondetta, allophane content is very low at all depths

PR in all soils and at all depths was highly correlated with acid oxalate extractable Al (Al_o) (r = 0.84*) and iron (Fe_o) (r = 0.89*). The sources of these 2 extracts (allophane and ferrihydrite) are largely responsible for the high PR in the soils studied. High allophane and ferrihydrite levels at all depths in Bialla soils correspond well with very high PR values (>90%) to at least 2 m depth. Low levels of these 2 minerals in Popondetta soils correspond well with low PR values (30%). Intermediate PR values (60 - 70%) for Hoskins and Kapiura surface soils correlates well with the occurrence of intermediate levels of allophane and ferrihydrite.

In all PNG soils, a P fractionation scheme showed that the major P fractions are organic. At Hoskins, NaOH-Po accounts for 38 to 48% of total P. For Kapiura NaOH-Po accounts for approximately 50% of total P, and Bicarb.-Po accounts for 59% of total bicarbonate-extractable P. For Bialla soils, NaOH-Po and Bicarb.-Po comprise between 74 and 76%, on average, of their respective total extracted P for all depths. At Popondetta, NaOH-Po comprises 62% and Bicarb.-Po 63% of their respective total extractable P contents.

P fertiliser accumulation in Hoskins and Kapiura soils occurs mostly in organic forms and within the top 10 cm of soil. At Hoskins, 83% of total added P accumulated in the top 10 cm (53% being NaOH-Po) while 17% was found in the next 10 cm depth (31% being NaOH-Po). At Kapiura, 74% of total accumulated P was found in the top 10 cm of soil (61% being NaOH-Po) and 26% within the 20 - 30 cm layer (81% being NaOH-Po).

The presence of amorphous minerals explains much of the behaviour of P in trial soils, with the major P source/sink in PNG soils being as organic forms.

In relation to soil mineralogical and chemical characteristics, PNG soils were classified into one of the major 3 groups in terms of responsiveness to P fertilisers; (a) soils with very high PR (>90%) and Olsen P values of less than 4 mg/kg which are considered most likely to respond to inorganic P fertilisers e.g. Bialla soil, (b) soils with medium to high PR (60 - 70%) will likely show inconsistent responses to P fertilisers and P responses are most likely to be secondary to N e.g. Hoskins and Kapiura soils and
(c) soils with low PR (30 - 40%) which are unlikely to respond to P fertilisers at least in the foreseeable future e.g. Popondetta soils.

This study highlights a future need for further study of the dynamics of P nutrient cycling, specifically the mineralisation rates of organic matter and the release of Pi for plant uptake in PNG oil palm growing soils. Also there is a need to re-establish the leaf critical concentration because in PNG soils though leaf levels are generally less than 0.150% DM, palms do not always respond to P fertilisers. This suggests that the "critical" P concentrations under PNG conditions is probably less than the international standard at 0.150% DM.

Mineralogical and P sorption characteristics of young volcanic ash soils in NZ are sufficiently similar to those in PNG to provide useful information about the general behaviour of P fertilisers and P reaction products in oil palm production systems.

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CHAPTER 1: INTRODUCTION

Phosphorus (P) is a very important plant nutrient element required by crops. P plays a number of very important roles in physiological functions of plants and P deficiency can severely retard growth and reduce crop yields (Mengel and Kirkby, 1987).

Despite the fact that P is essential important plant nutrient element, oil palm (*Elaies guineensis* Jacq.) grown on volcanic soils in Papua New Guinea (PNG) have generally shown no consistent response to P fertilisers. In most PNG soils, P appears to be secondary to nitrogen (N) as a limiting factor for oil palm production. Volcanic ash soils on which oil palm is grown in PNG are located near Hoskins, Kapiura and Bialla, all in West New Britain (WNB) in the Island Region, and at Popondetta in Oro Province on the mainland.

Oil palm grown in soils at Hoskins, Kapiura and Popondetta has not shown any significant responses to P fertilisers in yields and/or yield components. There is also no consistent increase in leaf P levels although leaf P levels are generally below the optimum of 0.15% DM. (Papua New Guinea Oil Palm Research Association (PNGOPRA) Annual Report, 1990). A notable exception to this general finding of lack of response to P occurs at Bialla where significant responses to P fertilisers both in yield and growth parameters were observed.

Forster (1990) suggested that some soil "factor" in volcanic soils was limiting the uptake of P by palms in these PNG soils but no research has been done to evaluate P characteristics of the common soils in PNG. This study is done on PNG volcanic soils from P fertiliser trial sites with the following aims:

1. To characterise PNG oil palm growing soils derived from volcanic ash parent materials by mineralogical and chemical analysis

2. To identify P fractions and their relative amounts in the soils

3. To determine the fate of applied P fertilisers in the soils

4. To compare the characteristics of PNG soils with New Zealand equivalent soils.

CHAPTER 2: LITERATURE REVIEW

2.1 OIL PALM GROWING SOILS

2.1.1 Introduction

Most of the soils in tropical areas are characterised by low pH and low inherent fertility (Swift and Sanchez, 1984). Though many of these soils are in this condition they are used extensively both for food and export crop production. Common tropical soils include Oxisols (23%), Ultisols (20%), Alfisols (15%), Entisols (16%) and Inceptisols (14%). The other soil orders are mostly less than 5% and Andisols comprise about 1% (Swift and Sanchez, 1984).

Hartley (1988) divided the world's oil palm growing soils into two general groups; soils developed on relatively stable landforms most of which are the latosols (Oxisols), and alluvial soils which are formed from a mixture of parent materials transported and redeposited by water. Major characteristics of these two main groups of oil palm soils are as follows:

2.1.2 Latosols

These soils are deeply weathered and situated on relatively stable landforms. The clay fractions have low silica:sesquioxide ratios due to intense weathering and leaching of silica and basic cations. They have low to medium cation exchange capacities, a relatively high degree of aggregate stability and low contents of primary minerals except for quartz. (Hartley, 1988). In other properties, latosols vary widely because of the different parent materials from which they are developed.

The latosols are common in inland soils of Malaysia, Africa and America on which oil palm is grown. In PNG, oil palm is mostly grown on Andisols.

2.1.3 Alluvial Soils

In South America and Asia, oil palm production occurs mainly on coastal and riverine alluvial soils. The soils have variable chemical and physical properties depending on the exact nature of the parent materials (Hartley, 1988). Many of these soils have drainage problems and high water tables are a common feature.

2.1.4 Oil Palm Growing Soils in Papua New Guinea (PNG)

PNG is different from most other tropical countries that have deeply weathered soils in that it is largely covered by slightly to moderately weathered soils mostly of mixed charges (potential and variable). Between 5 and 10% of PNG soils are Andisols; soils that are formed from volcanic ash materials (Bleeker and Sageman, 1990).

About 81% of the total hectarage on which oil palm is grown and 84% of total oil palm yield in 1995 comes from soils developed from volcanic ash (Oliver and King, 1996). Volcanic ash-derived soils occur at Hoskins, Kapiura, Bialla which are all in WNB Province and Popondetta which is on the mainland in Oro Province. Because of the good chemical and physical properties of these soils, along with high rainfall, these areas are highly suitable for oil palm production. Other plantations in PNG that produce the remaining 20 - 30% of the PNG oil palm crop are Milne Bay Estates in Milne Bay and Poliamba in New Ireland provinces. Soils in these 2 provinces are formed from nonvolcanic parent materials. In Milne Bay, soils on the terraces are formed from a mixture of parent materials including raised coral limestones while on the alluvial plains the soils comprise heavy clays that swell when wet and crack when dry and are associated with calcareous sediments (Bleeker, 1988). In New Ireland, soils are formed on raised coral reef bed terraces (Bleeker, 1983).

Soils of the major oil palm producing areas in PNG are discussed with emphasis on the field trial sites studied in this thesis.

2.1.4.1 Hoskins, Kapiura and Bialla

Hoskins, Kapiura and Bialla are located on the north coast of West New Britain province.

Soils at Hoskins and Kapiura are derived from 11 volcanoes in the Cape Hoskins area. The oldest recorded ash is about 2500 years old, from Mt. Galilo (Bleeker and Parfitt, 1974) and the latest is from the still active Mt. Pago which erupted in 1914 - 1918 (Blake and Ewart, 1974). In between these two eruptions there were other eruptions which have resulted in a number of buried horizons in the area.

Soils at Bialla are derived from ash from Mt. Ulawun, Mt. Bamus and Mt. Galloseulo (Hartley *et al.,* 1967). Other volcanic areas around Bialla include the Sulu Range and Hargy Volcano. Just as with the Hoskins area there has been a series of volcanic eruptions in the area from these volcanoes resulting in different soils being buried by subsequent ashes.

At Hoskins, Kapiura and Bialla, soil parent materials are either direct ash deposits, colluvium or alluvium (Hartley *et al.,* 1967, Zijsvelt, 1977 and Zijsverlt and Torlach, 1975). The soils at these sites are generally dark, high in organic matter, and have silty loam texture at the surface. At lower depths, the texture changes to loam or silty clay loam. This is probably due to either deep weathering and or movement of weathered clay from surface horizons to lower depths (Hartley *et al.,* 1967). Darker colours are seen at lower depths indicating the presence of buried horizons. At the lowest depths the soil materials are mostly pumice sand and gravel. Profile descriptions are as in Appendix 1 for Trial 107 in Hoskins and Appendix 2 for Trial 402 in Kapiura.

On the flood plain areas, soils derived from alluvial deposits are yellow brown in colour and range from loams to silty clay loams with no colour or textural changes down the profile. The soil materials in these areas are mostly comprised of topsoil materials that have been developed elsewhere, and transported to the present site by water. A representative profile description for a flood plain soil is shown in Appendix 3 for Trial 205 in Bialla.

Soil chemical properties for the volcanic ash soils at the trial sites are presented in Appendix 5 (PNGOPRA Annual Report, 1990).

Soils at Hoskins are generally slightly acidic with low to very low cation exchange capacity (CEC) (<13 meq%) but high base saturation; ranging from 64 to 90%. Olsen P values are generally very low, ranging from 2.7 to 9.7 mg/kg, and phosphate retention (PR) values range between 26 and 67% with a mean of 52% in the top 20 cm. pH in NaF ranges from 8 to 10.

The soils at Kapiura have similar chemical properties to those at Hoskins except for medium to high CEC and very high base saturation of around 90% in the top 20 cm.

At Bialla (Trial 201), the soils are slightly acidic with low to medium CEC (10.1 to 18.2 meq%) and medium base saturation (47 to 63%). Olsen P values are very low at less than 3 mg/kg with very high PR (> 90%) and high pH in NaF (> 10.4).

2.1.4.2 Popondetta Soils

Popondetta soils are derived from Mt. Lamington volcanic ash materials which erupted in 1951 (Bleeker, 1987). The soils on which oil palm is produced are divided into 2 major groups (in relation to landform type) viz. soils on the volcanic plains and on outwash plains.

Soils on the volcanic plains are mostly moderately weathered with generally well-developed dark topsoils. Soils on the outwash plains are redistributed colluvio-alluvial volcanic ash materials (Bleeker, 1987). Soils here in general, are loams to fine sandy clay loams with moderately-developed fine to medium subangular blocky structure. The A1 horizon merges into a very dark brown, very dark gray or very dark grayish brown transition, A3 horizon. Texture changes from sandy clay loam to fine sandy clay textures with firm but brittle consistency; texture becoming coarser with depth. A representative profile description is presented in Appendix 4.

Soils at Popondetta are slightly acidic with very low to low CEC values (3 - 14 meq %) and medium to very high base saturation (40 to 100%) (Appendix 5). Olsen P values are generally very low (<10 mg/kg) and the soils have low to medium PR values with a mean of 30% in the top 20 cm layer.

2.2 MINERALOGY OF SOIL PARENT MATERIALS

Volcanic ash materials are the main parent materials of soils in West New Britain and Oro Provinces. Volcanic ash materials, depending on their SiO_2 content can be classified as shown in Table 2.1 below (Shoji *et al.*, 1975)

Table 2.1 Total SiO_2 % Composition of Volcanic Ash Materials

Rock Type	*Rock*	*Total SiO_2 %*
Felsic (acidic)	Rhyolite	100 - 70
	Dacite	70 - 62
Intermediate	Andesite	62 - 58
	Basaltic Andesite	58 - 53.5
Mafic	Basalt	53.5 - 45

Source: Shoji *et al.*, (1975)

Volcanic ash materials in PNG are generally dacitic. Blake and Ewart (1974) reported that rocks in the Cape Hoskins area range in composition from basalt to rhyolite but most are andesites or dacites whereas rocks from Mt. Ulawun lavas around Bialla were basalt and low silica andesites. At Popondetta, Ruxton (1966) reported that the eruption of Mt Lamington in 1951, involved the disruption of green hornblende-bearing dacitic magma resulting in dacitic volcanic ash.

2.2.1 Primary Mineral Composition of Volcanic Ash Materials

Volcanic ash primary minerals can be grouped into 2 categories as light minerals and heavy minerals depending on their specific gravity (Dahlgren *et al.*, 1993). Light minerals have specific gravities of less than 2.8 - 3.0 and heavy minerals greater than 2.83.

Light minerals mostly dominate in volcanic ash making up 70 - 90% of the total primary mineral content (Shoji *et al.*, 1975). Of the light minerals volcanic glass is usually the commonest mineral followed by feldspars and silica minerals which include quartz and cristobolite.

Heavy minerals normally only make up a small fraction of the total minerals and include minerals like hypersthene, augite and hornblende. Ruxton (1966) and Pain (1971) reported that hornblende was a major heavy mineral in the ash from Mt. Lamington.

Accessory minerals also can be found along with the primary minerals. These include opals, cristobolite, kandites, allophane and smectified layer silicates which mostly are minerals formed from previous eruptions and formed on the walls of volcanic craters (Dahlgren *et al.*, 1993).

2.2.2 Secondary Clay Minerals in Volcanic Ash Soils

Common secondary clay minerals formed by weathering of volcanic ash materials include allophane, halloysite, imogolite and ferrihydrite (Dahlgren *et al.*, 1993).

2.2.2.1 Allophane

Allophane is a clay size mineral with short range order which contains silica, alumina and water in chemical combinations (Parfitt, 1990). There are 3 types of allophane and they are Al rich soil allophane, Si rich allophane and the stream deposit allophanes.

Of interest in crop production are the Al and Si rich allophanes. Both types of allophane occur together in soils with more of the Al rich than Si rich form (Parfitt, 1990).

Allophanes are very reactive because of their large surface area. Soil clay fractions containing allophanes show many discrete particles shaped as hollow spherules. The diameter of an individual spherule is about 4 nm and its wall thickness is about 0.7 - 1 nm (Hemni and Wada, 1976).

Al rich allophane is related to imogolite and has a Al:Si ratio of 2:1. It is also referred to as proto-imogolite allophane or imogolite-like allophane (Parfitt and Wilson, 1985).

The silica rich allophanes have a Al:Si ratio of 1:1. The Al in this mineral is present in octahedral sites with some in the tetrahedral sites (Kirkman, 1975).

2.2.2.2 Imogolite

Imogolite is commonly found with allophane and is similar to allophane in many of its chemical properties. Imogolite has a Al:Si ratio of 2:1 and is made up of bundles of fine tubes and has long range order. The wall of the tubes is about 7 nm thick and the outer surface is curved with hydroxyls at the surface. The inner surface consists of O_3SiOH tetrahedra with the oxygens replacing the inner hydroxyls of the octahedral layer. The structural formula is $(OH)_3Al_2O_3SiOH$.

2.2.2.3 Halloysite

Halloysite is a common constituent in volcanic soils and is common in silica-rich soil environment (Parfitt and Wilson, 1985). Halloysite is a 1:1 aluminosilicate mineral and has an interlayer of water molecules and a cylindrical structure.

2.2.2.4 Ferrihydrite

Iron in soils formed from volcanic ash is present mostly in the form of noncrystalline oxyhydroxides and partly as Fe-humus complexes (Parfitt and Childs, 1983). The dominant noncrystaline mineral is ferrihydrite which is a short range order Fe hydroxide with the chemical formula of $5Fe_2O_3.9H_2O$ (Schwertmann and Taylor, 1989). Ferrihydrite is highly reactive because of its hydroxylated surface and high surface area. It is also thermodynamically metastable and changes to other more stable Fe oxides.

2.2.3 Soil Weathering and Formation

Factors affecting the formation of volcanic ash soils have been reviewed by Lowe (1986) and formation of allophane and other soil minerals by Parfitt (1990).

The type of clay minerals formed from volcanic ash materials and their rates of transformation are mostly governed by macro and microenvironmental factors together with the mineralogical and physicochemical composition of the parent materials (Lowe, 1986). The macro environmental factors include rainfall and temperature while the microenvironmental factors are leaching regime, organic cycle, pH, drainage, vegetation, tephra thickness, depth of burial and additions of fresh tephra. The effect of time is usually secondary to environmental factors.

The environmental factors are very important because they determine the activity of silicic acid in the soil solution, the movement and availability of Al species and the opportunity to co-precipitate (Lowe, 1986).

These factors are discussed below.

2.2.3.1 Temperature

Higher temperatures promote higher rates of chemical reactions. PNG has a maximum temperature of 28 - 32 C, a minimum of 20 - 24 C and a mean of 26 C (McAlphine *et al.,* 1983). High temperatures occurring in PNG can result in high rates of weathering and formation of clay minerals. However, variation in rainfall, vegetation and depth of overburden coincide with temperature variations. Therefore temperature is only one of many factors that enhance weathering.

2.2.3.2 Rainfall, Leaching and Drainage

Rainfall and leaching play a dominant role in the weathering of volcanic glass minerals and in determining the composition of clay products (Lowe, 1986). High rainfall with good leaching promotes the formation of 2:1 allophane because of leaching of silica ions. On the other hand low rainfall and/or lack of leaching promotes formation of halloysite and 1:1 allophane minerals.

Formation of allophane and halloysite in PNG soils is very rapid because of high rainfall. Rainfall in PNG ranges from 2000 to 4000 mm per year (McAlphine *et al.,* 1983). In 1990, total rainfall at Hoskins, Kapiura and Bialla was 4500 mm whilst Popondetta had 3061 mm (PNGOPRA Annual Report, 1990). Allophane in Hoskins soils has been reported to transform to halloysite within 300 years compared to the 8000 - 9000 years needed in temperate countries (Bleeker and Parfitt, 1974).

Slow drainage and a stagnant moisture regime results in small losses of silica and cations. This favours the formation of halloysite and silica-rich allophane (1:1 allophane). Good drainage promotes the formation of 2:1 allophane. Parfitt *et al.,* (1984) studying New Zealand soils for the effect of soil moisture on the formation of allophane and halloysite in volcanic ash soils dated at 20,000 years concluded the following:

- where drainage is ≤ 250 mm a year, halloysite is formed in considerable amounts,
- where drainage is > 200 mm, allophane is present in considerable amounts and
- the Al/Si mole ratio of allophane increases from 1.2 to 2.1 as leaching increases from 250 to 600 mm per year.

Generally, allophane is formed in soils with pH greater than 4.8 (Parfitt and Kimble, 1989) and where Si concentration is less than 10 g/m^3 (Singleton *et al.*, 1989).

Halloysite is usually present in older tephras and it has been suggested that with time allophane weathers to form halloysite. However Kirkman and McHardy (1980) reported that halloysite can form directly from weathered volcanic glass where silica activity is high, as in rhyolitic tephra as compared to andesitic tephra.

2.2.3.3 Tephra Thickness and Depth of Burial Effect

When developed soils are buried by subsequent ashes or alluvial deposits, pedological processes are affected (Ruxton, 1968). For instance buried horizons reduce organic matter input and allow Al previously bound by organic matter to be released over time by weathering. Al then reacts with Si to form allophane and imogolite. Silica enrichment from surface soils by leaching will favour the formation of halloysites (Lowe, 1986).

2.2.3.4 Organic Cycle Effects

Soils developed from volcanic ash materials characteristically contain high organic matter contents.

Al and Fe form complexes with the organic matter and this suppresses the activities of Al and Fe ions. The potential for Al and silica bonding is reduced, leading to lower allophane in A1 horizons than at lower depths in some soils. Silica then forms opaline, especially in relatively young volcanic ash soils (Parfitt, 1975).

2.3 REACTIONS OF PHOSPHORUS IN SOILS

Many soils in the tropics have been subjected to intensive weathering processes due to the high rainfall and temperature in these regions. These processes result in permanent changes in the soils' mineralogical and chemical properties. In most cases the original minerals and their permanent charges have been weathered out and new surface charges are developed from adsorption of potential determining ions. The charges on the mineral surfaces depend on the ambient solution pH and minerals are normally referred to as having pH-dependent or variable-charge (Uehara and Gillman, 1981).

2.3.1 Permanent and Variable Charge Clay Minerals

Surface charges of soil minerals can be divided into 2 groups, permanent and variable charges (McLaren and Cameron, 1996). The charges are very important in that they determine the adsorption/desorption characteristics of mineral nutrients (cations and anions) and their availability in the soil solution for crop uptake .

2.3.1.1 Permanent Charge

Permanent charges on soil colloids arise from isomorphous substitution of cations in the lattice structures of clay minerals. When a cation of a lower valency e.g. Mg^{2+} substitutes for a cation of a higher valency e.g. Al^{3+} this creates a net negative charge on the mineral surface. On the other hand if a cation of a higher valency substitutes for one of lower valency cation a net positive charge is created. The negative charges created are neutralised by the presence of cations in the interlayers of the minerals. (McLaren and Cameron, 1996).

2.3.1.2 Variable Charge

Variable charge on clay surfaces is formed by the displacement of H^+ and OH^- ions at the edges of clay minerals and by the behaviour of functional groups on organic matter (McLaren and Cameron, 1996).

The amount of charge is pH dependent, i.e. controlled by the relative concentrations of H^+ and OH^- ions in the ambient solution. As pH increases i.e. there is an increase in the OH^- ion concentration, negative charge on soil colloidal surface increases. This results in an increase in cation exchange capacity of a soil. In contrast, as pH decreases, i.e. there is an increase in the H^+ ion concentrations, the negative charge decreases and the positive charge increases. This results in an increase in anion exchange capacity (AEC) of a soil. Hence pH is very important in determining the CEC and AEC of soils. The amount of charge is also affected by the ionic strength of the ambient solution.

Many soils in the tropics, including Oxisols and Andisols, contain variable charge clay minerals. These minerals mostly contain Fe and Al oxides and hydroxides and short range order aluminosilicates (allophane and imogolites).

In soils, the pH at which the number of positive charges is equal to the number of negative charges is known as the point of zero net charge (PZNC) (McBride, 1994). In soils with pH dependent charge, when the soil pH is below the pH (PZNC), the soil has a net positive charge but when the pH is raised above the pH (PZNC), the charges become net negative. The pH (PZNC) of a particular soil depends on the nature of the variable charge minerals and organic components. Soils high in oxides and hydroxides of Fe and Al and short range order aluminosilicates and 1:1 clays have pH (PZNC) ranging from pH 6.5 to 9.5. Such soils will be positively charged at normal soil pH and have high AEC. Soils high in organic matter and 2:1 clay minerals on the other hand, have low pH (PZNC) and are highly negatively charged, resulting in high CEC.

These characteristics of soil minerals are very important in determining the availability of cations and anions in soils.

2.3.2 Phosphate Adsorption

Phosphate (P) ions can be adsorbed onto the surfaces of several types of minerals present in the soils, either as discrete particles or as coatings on other minerals (McLaren and Cameron, 1996). The common minerals involved include Fe and Al oxides and hydroxides and the short range order alumininosilicate minerals (McBride, 1994). The oxides and hydroxides of Fe include goethite and ferrihydrite and for aluminium, gibbsite. The short range order alumino silicate minerals include imogolite and allophane. These minerals have amphoteric surfaces which means that they develop either negative or positive charges on their surfaces, depending on the ambient soil solution pH.

Adsorption of P ions onto minerals takes place by specific adsorption, but simple anion exchange on the positively charged sites can also take place and is probably important in the initial stages only; especially in high PR soils. Adsorption of P onto the soil minerals involves ligand exchange and this happens when the P ions displace water and/or OH groups bonded to Al and Fe ($FeOH^{2+}$, $Al\text{-}OH^{2+}$, $Fe(OH)_2^+$ and $Al\text{-}(OH)^+$). In the process 3 different types of bonding can result; monodentate, bidentate and binuclear (Fixen and Grove, 1990).

2.3.2.1 Adsorption Mechanisms of Phosphates on the Variable Charge Surface Clay Minerals.

Adsorption mechanisms on the variable charge clay minerals have been summarised by Parfitt (1978 and 1989). Some of the common minerals and adsorption of P mechanisms involved are discussed briefly below:

2.3.2.1.1 Allophane

Parfitt (1988) suggested 3 mechanisms could be involved in the reaction of P with allophane minerals.

a) First, P is rapidly and strongly adsorbed by ligand exchange on the most reactive AlOH defect sites. At these sites either monodentate or binuclear complexes are formed. P ions here are strongly bonded and are not available for plant uptake, at least in the short term.

b) As the amount of P adsorbed increases, adsorption occurs onto less reactive defect sites. Such P is readily available for plant uptake.

c) Finally, with time or with higher P concentrations, P reacts with more Al, probably also at the defect sites. When aluminum phosphate precipitates are formed the allophane structure is disrupted and new defect sites are created. This P is probably not available for fast growing crops.

P cannot diffusively penetrate the allophane minerals if all the AlOH groups are exposed at the surface. Also it is unlikely that P ions can diffuse through an Al-P coating because this would lead to a disruption of the allophane structure which is only 3 atoms thick and which cannot support coatings (Parfitt, 1989)

When studying loss of available P in New Zealand soils, Parfitt *et al.,* (1989) showed that when 700 mg P/kg was added to allophanic soils (Andisols), about 100 mg P /kg was strongly adsorbed, about 200 mg P /kg became unavailable within 200 days and the remainder was weakly adsorbed. In Inceptisols containing ferrihydrite and Al-humus as predominant reactive species, similar results were observed. In Oxisols where 600 mg P /kg was added, 150 mg P/kg became unavailable with time as a result of reaction with iron oxides and Al-humus.

2.3.2.1.2 Iron Oxides

The reactive surfaces and the crystallinity of the oxides determines the reactions of iron oxides with P. The reactions first are probably rapid and involve strong ligand exchange, followed by weaker ligand exchange and by penetration at the defect sites and pores. Under very acidic conditions, precipitates of iron phosphates can be formed (Parfitt, 1989).

2.3.3 Phosphorus Desorption.

Depending on the type of bonding between P and the soil clay minerals the phosphate ions can move into the solution pool and become available for plant uptake. Generally, however, the process of desorption is very slow compared to adsorption reactions. P sorption by binuclear bonds is relatively irreversible and cannot be made available for plant uptake whereas P bonded by monodentate and bidentate mechanisms can be desorbed and become available for crop uptake (Parfitt, 1977).

2.3.4 Phosphate Retention (PR) Tests

PR tests are used to determine the capacity of a soil to retain P. This does not tell about the type of bonding nor the mechanisms involved but does give an idea of potential P availability in a soil.

Factors that influence PR of soils include, nature of soil minerals, pH, other anions and cations, organic matter and soil water status (Tisdale *et al.,* 1985 ; Sanyal and Datta, 1991).

2.4 PHOSPHORUS FORMS IN SOILS

The major source of all soil P is primary apatite minerals (Smeck, 1985). Examples of some of the common apatite minerals are shown in Table 2.2.

Table 2.2 Examples of Common Primary P Minerals

Mineral	*Chemical formula*
Fluorapatite	$3Ca_3(PO_4)_2 . CaF_2$
Hydroxyapatite	$3Ca_3(PO_4)_2 . Ca(OH)_2$
Carbonate apatite	$3Ca_3(PO_4)_2 . CaCO_3$
Chlorapatite	$3Ca_3(PO_4)_2 . CaCl_2$

Source: McLaren and Cameron, 1996

During the process of weathering, P is released into the soil solution. This soluble P may become adsorbed to soil clay mineral surfaces, precipitated with various cations and/or incorporated into biomass and soil organic matter (Tiessen *et al.*, 1984).

Soil P mineralogy and chemistry are complex, and this makes direct analysis and characterisation of the different P forms that are formed during soil development difficult. Selective dissolution techniques have been used to characterise soil inorganic-P (Pi) (Chang and Jackson, 1957), organic-P (Po) (Bowman and Cole, 1978b) and plant available P (Dalal and Hallsworth, 1976). Hedley and co-workers (Hedley *et al.*, 1982) developed a sequential extraction procedure that was able to characterise the labile and more stable Pi and Po forms.

With the Hedley P fractionation procedure, the most labile P is extracted from a soil using a combination of anion and cation exchange resins. Other forms of labile, nonlabile, nonoccluded and occluded inorganic and organic-P are removed sequentially using a series of successively stronger extractants as summarised below.

a) Resin-extractable Pi (Resin-Pi) and Bicarbonate-extractable Pi (Bicarb.-Pi) are taken to be labile Pi loosely adsorbed on surfaces of minerals, sesquioxides or carbonates (Tiessen *et al.*, 1984). Such Pi is considered readily available for plant uptake (Hedley *et al.*, 1994) and microbial use (Cross and Schlesinger, 1995).

b) Bicarbonate-extractable Po (Bicarb.-Po) is a measure of easily mineralisable organic-P which probably contributes to the relatively short-term plant available pool (Bowman and Cole, 1978b).

c) NaOH-extractable Pi and Po (NaOH-Pi and NaOH-Po) represent P that is not readily available, being strongly associated with amorphous minerals and some aluminum and iron phosphates.

d) Acid-extractable Pi (H_2SO_4-Pi) includes P largely Ca-bound P and lattice P.

e) Residual P is probably remaining occluded Po and Pi covered by Fe and/or Al oxyhydroxides and therefore not readily available for plant uptake.

The major problem with P supply to plants is that most of the soil P is held in insoluble form in the "nonlabile" pools which includes both inorganic and organic forms.

2.4.1 Soil Inorganic P Fractions

Movement of P from one pool to the other is highly pH dependent (Mengel and Kirkby, 1987). In strongly acid soils (pH 3 and 4) most of the P is chemically-sorbed onto Al, Fe, Mn or Mg oxides and hydroxides. This effectively moves P into a nonlabile form and makes it less available for plant uptake. The phosphorus form involved is $H_2PO_4^-$ (orthophosphate). As the pH increases towards 5 and 6, OH^- ions displace the P ions which are then likely to be adsorbed by Al, Fe, Mn and Mg oxy/hydroxides. The P in the labile pool is held on soil mineral surfaces in rapid equilibrium with soil solution. Therefore, when P in solution is taken up by plants, or soil microorganisms, it is replaced from the labile pool and a new equilibrium establishes between surface and soluble P.

At pH 6.5 more adsorbed phosphate ions become readily available for plant uptake (Brady, 1978). At this pH the concentration ratio of $H_2PO_4^-$ to HPO_4^{2-} is approximately 1:1 (Mengel and Kirkby, 1978).

As the pH increases further to 7 and 8, P is again sorbed but this time onto calcium ions as calcium phosphates. Here the phosphate ions are moved back into a nonlabile pool and become relatively unavailable for plant uptake.

2.4.1.1 Reactions of P Fertilisers in Soils

Sanyal and Datta (1991) and Tisdale *at al.,* (1985) reviewed chemical reactions between P fertilisers and soils. The following information was derived mainly from these sources.

The effectiveness of P fertilisers in soils is determined by soil and fertiliser properties and reactions between the two. When soluble P fertilisers are applied to a soil, rapid dissolution of the granules occurs. Water from areas around the granules moves into the fertiliser granules to initiate the dissolution process. This solution soon becomes saturated with P fertiliser salts and this creates an osmotic potential gradient between the fertiliser granules and the soil water. While water is drawn in by the fertiliser, soluble salts move outwards. This continues (dilution) until the soil solution reaches a new equilibrium composition.

Several changes in the chemical properties of soils take place during the dissolution process. The environment immediately around the P fertiliser is dominated by the solution properties which over-ride the original soil properties. Because of the differences in the component of different fertilisers marked differences in reactions occur in the zone surrounding the fertiliser granules. This high P, low pH, solution can dissolve soil minerals , lower soil pH and may result in the release of reactive cations (Fe^{3+}, Al^{3+}, Mn^{2+} and Mg^{2+}). The cations released may later participate in P sorption as the pH moderates.

2.4.2 Soil Organic P Forms

The nature and reactions of organically-bound P are not as fully understood as those of inorganic P (Tisdale *et al.,* 1985). However many soils contain between 20 - 80% of their P in the organic form (Dalal, 1977). Most of this organic-P is in the soil surface horizons for obvious reasons. Organic P usually decreases with depth but can be relatively constant in recent alluvial and peaty soils.

Most of the organic P in soils is from residual plant materials including dead leaves and roots and microbially synthesised materials.

2.4.2.1 Factors Influencing Organic P Contents

Factors that influence organic matter content of a soil also influence P content. Walker and Adams (1959) showed that the P content of organic matter decreased as rainfall and mean temperature increased. Other factors include drainage, soil pH, crop cultivation, inorganic P content of the parent material and availability of other nutrient elements.

2.4.2.2 Nature of Soil Organic P Compounds

Soil organic P is generally classified into 3 groups; (1) inositol-P, (2) phospholipid-P and (3) nucleic acid-P (Anderson, 1980). There is still a large proportion of soil organic P that is unidentified and probably exists as insoluble complexes with clay minerals and organic matter (Tate, 1984). The three common identified groups are now briefly discussed.

2.4.2.2.1 Inositol Phosphates

Inositol-P is the dominant Po compound (Anderson, 1980). It is made up of a monocyclic sugar-like compound which forms a series of P esters ranging from monophosphates through to the hexaphosphate phytic acid (Tisdale *et al.*, 1985).

These P esters are released from organic substances in soils at a much slower rate than many other esters and are quickly stabilised. They are more resistant to enzymatic attack than other P forms. The accumulation of inositol P in soils is thought to be due to its capacity to form insoluble precipitates with Fe, Al and Ca and become strongly adsorbed onto amorphous Fe and Al oxy/hydroxides (Duxbury *et al.,* 1989). They are a major P form and usually account for more than 50% of total organic P in a soil.

2.4.2.2.2 Phospholipids

Phospholipids are actual or potential esters of fatty acids (Tisdale *et al.,* 1985). Lecithin and phosphatidylethanolamine are the predominant phospholids in soils although together they comprise less than 15% of the total organic P (Duxbury *et al.,* 1989). Phospholipids are released rapidly from soil organic matter during mineralisation.

2.4.2.2.3 Nucleic Acids

Nucleic acid-P is mostly in the form of ribonucleic acids (RNA) and deoxyribonucleic acids (DNA) or their derivatives. The source of nucleic acid is mostly from decomposing microbial, plant and animal remains.

In soils, nucleic acids are rapidly mineralised and incorporated into microbial biomass and they comprise less than 5% of the total organic P in soil (Duxbury *et al.,* 1989).

2.4.2.3 Organic P Turnover

Po is part of organic matter and therefore follows general patterns of accumulation and loss of organic matter as a whole.

The build up of soil organic P is called "immobilisation". In the process of immobilisation, P in soil solution is biologically converted to organic P compounds. The conversion of Po to Pi is referred to as "mineralisation" and is also done biologically. Both immobilisation and mineralisation take place at the same time in soils and only the difference in their rates can be noticed at any one time (Dalal, 1977).

Various factors influence the rates at which these two processes occur and subsequently affect the supply of readily-available Pi.

2.4.2.3.1 Immobilisation / Mineralistion

As discussed earlier, during the process of soil development a considerable amount of Pi is converted into organic forms. The P content of the soil parent materials determines the build up of organic matter when all other plant nutrients are in sufficient amounts (Walker and Adams, 1958). The P content of the parent materials is therefore a major factor governing the accumulation of P in the resultant soils. Close relationships have been observed between organic P and total P (Walker and Syers, 1976 and Syers and Walker, 1969).

In Australia where native Pi is low, inorganic P fertiliser application has been shown to cause an increase in soil organic P (Jackson, 1966). Perrott *et al.,* (1989) studying P accumulation in Yellow Brown Pumice soils in New Zealand reported the build up of more labile Po forms which increased curvilinearly with total P while other P fractions increased linearly. The curvilinear response indicated that the build up approached an equilibrium value. An increase in Po as well as organic matter, is via increased plant growth which contributes the dry matter together with increased microbial activities.

Organo-mineral complexes, especially in volcanic ash soils, can accumulate and in the process render Pi unavailable for plant uptake. Volcanic soils often contain large amounts of organic matter and P can be "locked-up" in this way.

Addition of organic materials with large C to P ratios increases microbial activity and this results in the formation of Po from Pi in the soil (Dalal, 1977). The C:Po ratio of plant residues and soils is very important in determining the formation of Po. A concentration of P in organic matter of 0.2% is critical for immobilisation and/or mineralisation. Where C:Po ratio is less than 200:1, Po is mineralised but if the ratio is greater than 300:1, immobilisation of P can occur (Dalal, 1977). P accumulation is also governed by other environmental factors and nutrient supply.

Organic-P in soils contributes P to plants after being mineralised to Pi. Mineralisation of Po to Pi is largely due to the combined activities of soil microorganisms and free enzymes (phosphatases; exo and intracellular). Soluble-P released by mineralisation is subject to sorption and therefore availability to crops can be reduced (Anderson, 1980). Factors that influence the activities of microbes also affect the mineralisation processes.

Important factors influencing mineralisation processes include temperature, soil moisture, aeration, soil pH, addition of inorganic P fertilisers and other fertilisers, cultivation practices, soil microorganisms and presence of crops (Dalal, 1977). These factors also govern crop growth and production in soils.

2.4.2.4 Organic-P as P Source for Crops

A decrease in organic P in cultivated soils has been reported by various researchers (Tiessen *et al.,* 1982 and Tate, 1984). Crop cultivation with good drainage and adequate aeration encourages microbial activity and can result in an increase in organic matter decomposition rate (Dalal, 1977). The more easily mineralisable Po such as nucleic acids and phospholipids are usually mineralised more quickly than inositol P (Hawkes *et al.,* 1984).

Tiessen *et al.,* (1983) and Bowman and Cole (1978b) observed that labile Po extracted with bicarbonate was rapidly depleted following cultivation whilst at the same time there was a corresponding increase in bicarbonate Pi. The reduction in Po was associated with a decrease in soil organic matter content.

A significant contribution of organic-P to crop nutrition has been reported in the tropics where soil organic P is often the major source of P. Poor relationships between crop responses to inorganic P fertilisers were seen in several regions of Africa and with various inorganic P soil test measurements which work in other areas (Anderson, 1980). Better overall correlations in East African soils between total soil organic-P and wheat crop responses were reported by Friend and Birch (1960). They related crop response to PR capacity and soil organic P content and suggested that responses to inorganic P fertiliser were unlikely when total organic P was greater than 640 ppm. Similar relationships in Ghana and Nigeria were seen between cocoa responses and soil organic P (Smith and Acquaye, 1963 and Omotso, 1971). Cocoa response to inorganic P fertilisers decreased as soil organic-P increased up to 300 ppm and there were no P responses found in soils above 445 ppm organic P. These situations illustrate the importance of soil organic-P as an important source of P to crops where even conventional soil P tests indicate very low levels of P.

2.5 PHOSPHORUS NUTRITION OF OIL PALM

2.5.1 Oil Palm Responses to Inorganic P Fertilisers

Oil palm responses to P fertiliser applications are generally secondary to N and K. In most soils responses to P are only seen after N and K requirements have been met. Forster (1990) reported no obvious relationships between oil palm responses and soil P tests in volcanic ash soils.

Despite the fact that phosphorus is a very important nutrient element required by most crops for good growth, there is a general lack of response to P fertiliser treatments in volcanic derived soils in PNG (PNGOPRA Annual Report, 1991). The following discussion relates results from PNGOPRA field trials to responses to phosphorus fertiliser in volcanic ash soils in PNG and in other parts of the world. The PNG findings have been extracted from PNGOPRA Annual Reports over the period 1982 to 1991.

2.5.1.1 P Responses in PNG

2.5.1.1.1 Hoskins Trials

In general trials at Hoskins showed no consistent yield responses to P fertilisers applied as TSP.

In trial 107 accumulated data from 1988 to 1990 did not show any yield responses to P and the only positive response found was an increase in leaf area index from 6.278 to 6.669 ($p = 0.001$) in 1990 (Table 2.3). However this significant growth result was not translated into yield responses.

In other trials at Hoskins, similar P results are reported. Soil nitrogen appears to be the main limiting nutrient and only when N requirements have been met, will the need for other nutrients such as P and Mg arise.

Table 2.3. PNG Field P Fertiliser Trial Results, January 1988 to December 1990

Sites	*Treatments TSP (kg/plm/yr)*	*FFB (t/ha/yr)*	*Bunches (#/ha/yr)*	*SBW (kg)*	**Leaf P level (% DM)*	*Leaf Mg levels (% DM)*	**LAI*
Hoskins	0	27.16	2011	13.52	0.149	0.152	**2.278**
(107)	1.0	27.09	2036	13.32	0.150	0.153	**6.357**
	2.0	27.25	2009	13.60	0.150	0.146	**6.669**
Kapiura **	0	16.71	1960	8.58	0.158	0.182	----
(401)	2.0	16.87	1985	8.54	0.161	0.185	----
	4.0	16.05	1949	8.28	0.162	0.188	----
Bialla	0	**17.52**	**828**	**21.23**	**0.132**	**0.116**	----
(201)	2.0	**19.05**	**882**	**21.62**	**0.137**	**0.123**	----
	4.0	**20.16**	**918**	**22.04**	**0.138**	**0.124**	----
Popondetta	0	28.4	1391	20.5	0.140	0.166	----
(305)	2.0	28.5	1405	20.2	0.143	0.162	----
(306)	0	25.0	1226	20.3	0.146	0.219	6.6
	0.5	24.6	1193	20.6	0.146	0.224	6.7
	1.0	25.2	1211	20.9	0.147	0.217	6.5

Source: PNGOPRA Annual Report, 1990

* only for 1990
** all 1990 results only
FFB = Fresh fruit bunch weight
SBW = Single bunch weight
LAI = Leaf area index

2.5.1.1.2 Kapiura

Trials at Kapiura were only recently established at the time of the PNGOPRA report but there is early evidence in Trial 401 to suggest that TSP increases P leaflet levels (from 0.158 to 0.162 % DM) though not statistically significant (Table 2.3). Because the palms are still young, P levels are higher than the optimum of 0.15% DM. The critical leaf level for P is 0.150% DM (Ochs and Olivin, 1976). The 1995 PNGOPRA General Proposal Report indicates no yield response from TSP but N and Mg responses have been found.

2.5.1.1.3 Bialla

Trial 201 at Bialla was the only trial in PNG that showed consistent significant, responses to P fertiliser application (Table 2.3). Accumulated data from 1988 to 1990 indicated that yield was significantly increased from 17.52 to 20.16 t/ha/yr ($p = 0.05$). This response was due to significant increases in both the single bunch weight ($p = 0.032$) and the number of bunches ($p = 0.035$). In 1990, P fertilisers also increased leaf P levels from 0.132 to 0.138 % DM ($p = 0.001$) and Mg from 0.116 to 0.124% significantly ($p = 0.044$).

Other combinations of fertilisers without TSP had no effect on either leaf P or Mg levels or yield. This indicates that P may be a major limiting nutrient in the Bialla soils.

2.5.1.1.4 Popondetta

Trials 305 and 306 which are the two major long term fertiliser trials at Popondetta, generally showed no significant yield or leaf P levels responses to P fertilisers (Table 2.3).

In trial 305 there was a significant NxP interaction ($p = 0.05$). P addition caused a yield increase in the presence of N but not in the absence of N. The interaction was especially apparent in the early years of this trial but disappeared in the later stages.

The palms were 12 years old in 1990 at the time of reporting. There were also responses to P in the leaf P levels but these were not significant and were generally in the range of 0.135 to 0.144% which is below the optimum of 0.15% DM.

Overall, the Popondetta trials showed no significant responses to P fertilisers alone but sporadic, inconsistent effects were observed in the presence of N.

2.5.1.2 Oil Palm Responses to P Fertiliser Applications in Other Parts of the World

In other parts of the world, oil palm responses to P fertiliser applications are usually secondary to N and K fertiliser responses.

In Malaysia on both inland and coastal soils, Zakaria and others (1991) reported responses to P only in the presence of nitrogen. Large P responses were observed in new plantings on low inherent P fertility areas cleared from the jungles.

In Belem, near the mouth of the Amazon River in Brazil, Martin and Preoux (1972) reported the only outstanding case of a P deficient (total P of 80 ppm) soil that showed a significant response to P fertiliser application. This trial showed very poor growth and low yields in the absence of P but significant P responses were seen when P was applied over a number of years. P applications also increased the uptake and levels of other nutrients in the leaflets.

2.5.2 Physiological Roles of Phosphorus in Oil Palm

P has a number of very important physiological functions in plants. Soon after uptake by plants P is transformed into organic P compounds. The organic P compounds are mainly hexose phosphates and uridine diphosphates (Mengel and Kirkby, 1985). From these two compounds, all other P-containing compounds are formed. They have very important roles in the plant metabolism. The most important function of organic P compounds are summarized by Mengel and Kirkby (1985) as follows:

2.5.2.1 Energy Transfer

All metabolic activities in plant cells need energy to function. The energy storage system is adenosine triphosphate (ATP) which is formed from an inorganic phosphate and adenine diphosphate. The P groups are bonded to each other by bonds that are energy-rich.

ATP is formed during photophosphorylation, oxidative phosphorylation and during anaerobic carbohydrate breakdown processes. Upon hydrolysis, ATP releases 32 kJ/mole of ATP (Mengel and Kirkby, 1985). The energy released is used for synthesis of other organic molecules and uptake and transport of certain ions.

2.5.2.2 Genetic Functions

Phosphorus is also an important component of proteins involved in the transfer of genetic information in living cells. The phosphate group in nucleic acid bridges the ribose and deoxyribose with another ribose or deoxyribose by two ester bonds to form ribonucleic acid (RNA) and deoxyribonucleic acid (DNA) respectively.

These compounds, are very important in carrying the genetic information for creating new cells and passing on genetic information to the next generation of plants.

2.5.2.3 Cell Structural Components

Phosphate forms a diester linkage with phospholipids and examples of such compounds are lecithin and phosphatidyl ethanolamine which are very important components of biological cell membranes.

These compounds have very important functions in the root cells in terms of uptake of plant nutrients from soil solution and the maintenance of cell pH.

2.5.2.4 Storage in Seeds

For a germinating seed, energy is needed at the early stages of growth. Phosphates provide this energy and are stored in reserves, in seeds, as phytins. Phytins occur in seeds as salts of Ca and Mg (Marchner, 1995). The P stored here is important because in the early stages of a plant growth when a seed is germinating it is not in a position to photosynthesize or to take up nutrients for growth.

2.5.3 Effects of Phosphorus Deficiency

Visible symptoms of P deficiency of oil palms are rarely seen in the field. In pot culture the oldest leaves become dull and assume an olive pale colour. In Belem, in Brazil, poor growth of oil palms and very low yields were observed (Martin and Preoux, 1972) under P deficient conditions.

Generally, in plants if there are any visible signs of P deficiency they normally occur on older leaves as dark green colours due to enhanced formation of anthocyanin (Hartley, 1988). This normally happens because of remobilization of P from older to younger leaves, reproductive organs, developing seeds and roots. Senescence of P-deficient leaves may occur earlier thus lowering the plant's photosynthetic capacity.

Because P is involved in very important physiological functions, deficiency can result in a general reduction in the plant metabolic functions which include cell division and expansion, respiration and photosynthesis (Terry and Ulrich, 1973). P deficiency also influences the starch /sucrose ratio in the source leaves and their eventual distribution to the reproductive organs. This can result in poor seed production as well as abortion of pollinated flowers.

P is also important in the uptake of other plant nutrients and a deficiency of P can result in reduced uptake of other plant nutrients. Therefore an N, or K, or Mg deficiency may result; but this is induced by the P deficiency. P deficiency in seeds can result in poor seedling germination.

2.5.4 P Concentration in Oil Palm Leaves

The use of chemical analysis of plant tissue for monitoring plant nutrient levels is based on the assumption that there exists a causal relationship between growth rates and nutrient content in the shoot dry, or fresh matter or concentration in the tissue, sap or some plant tissue (Marschner, 1995). The relationship is usually referred to as the nutrient response curve. Plant tissue analysis is done to determine, amongst other things, the critical nutrient concentration. The critical nutrient concentration within some plant part is that level below which growth or crop yield is restricted (Bates, 1971). The critical level is normally selected at 80 - 90% of maximum yield depending on the level of management and inputs.

The critical nutrient concentrations for oil palm published by IRHO for the major nutrients in leaf 17 of mature palms are shown in Table 2.4 below.

Table 2.4 Critical Nutrient Concentration in Oil Palm Leaf (IRHO Trials)

N	P	K	Mg	Ca
2.5%	0.15%	1.0%	0.24%	0.6%

Source: Ochs and Olivin, 1976

In Malaysia the ranges for the concentrations for optimum yield at 25t/ha/year are as follows for a range of soils (Jones - Bole, 1975).

Table 2.5 Critical Nutrient Concentration in Oil Palm Leaf (Malaysian Trials)

N	P	K	Mg	
2.6 - 2.7	0.15 - 0.17	1.1 - 1.2	0.27 - 0.29	Young coastal clay soils
2.5 - 2.6	0.15 - 0.17	1.0 - 1.1	0.25 - 0.26	Old coastal clay soils
2.5 - 2.6	0.15 - 0.17	1.0 - 1.1	0.23 - 0.25	Young upland soils
2.5 - 2.6	0.15 - 0.17	0.9 - 1.0	0.23 - 0.25	Old upland soils

Source: Jones - Bole, 1975

The ranges are remarkably similar for all soils in Malaysia and do not vary very much between the IRHO and Malaysian conditions. Results provided as a range (e.g. sufficiency range) are better than a single critical value. The optimum range for phosphorus is 0.145 - 0.17% DM and the best estimate of the recommended critical value is around 0.15% for oil palm (Ochs and Olivin, 1976).

Trials in West New Britain and in Popondetta generally showed very low levels of P in the fronds; mostly below 0.15% DM (PNGOPRA Annual Report, 1991). In many of the fertiliser trials done in PNG, P fertilisers have not produced even increases in the leaf P levels which suggests either:

a) the critical level is lower in PNG than elsewhere

b) other factors are even more limiting in PNG than elsewhere

c) P fertiliser is not accessed by the roots of oil palm in PNG or

d) the soil restricts P uptake after fertiliser applications

Some of these possibilities are discussed later in the thesis.

2.5.5 General Description and Functions of Oil Palm Root System

General characteristics of the oil palm root system have been reviewed by Tinker (1976). Oil palm has an adventitious root system. First are the primary roots, of 6 - 10 mm diameter, which are borne out from the trunk base and spread horizontally or vertically at varying angles into the soil. From the primary roots, secondary roots with diameters of 2 - 4 mm branch out carrying tertiary roots which are 0.7 - 1.2 mm in diameter. The tertiary roots then carry the quaternary roots which are unlignified with diameters of 0.1 - 0.3 mm and 1 - 4 mm long. It is the quaternary roots which are assumed to be the main absorbing parts. The fine quaternary roots can penetrate soil pores enhancing the palm's ability to search for plant nutrients.

Oil palm root systems are mostly superficial, rarely going deeper than 1m into the soil. Except for the primaries, roots lie fairly close to the soil surface and are most active probably in the top 15 to 30 cm (Omoti and Ataga, 1978). Most of the secondary roots can go down to a depth of 1.5 m in deep soils. Horizontally, the roots can grow to a distance of about 20 - 30 m from the base of the palm. Soil moisture, soil pans, depth to water table and soil fertility affect root distribution, both horizontally and vertically (Omoti and Ataga, 1978). High water tables, especially in low lying areas, can limit the depth to which palm roots grow but can be beneficial during dry months of the year.

2.5.6 The Oil Palm Phosphorus Uptake

The P requirement of oil palms change with age. Tinker and Smilde (1963) observed that P uptake is small in comparison to that for K and Mg. A large proportion of the P is diverted to fruit bunches and this amount is removed with the fruit bunches during harvesting. They also reported that P immobilization in the palm is small in comparison to K and Mg and the large amount that is removed with the fruits requires a good supply from soils or from fertilisers to produce high yields. Even if P is remobilised from older fronds to meet the demand created by removal of harvested bunches, there will still be a deficit if higher yields of 24 to 26 tonnes per hectare per year are to be achieved.

There are 3 types of demand for plant nutrients that need to be taken into account in nutrient budgets to determine requirements of oil palm crops (Tinker, 1976):

a) nutrients removed permanently, as in the harvested fruit bunches,

b) nutrients taken up by the palms, but immobilized in the palms and

c) nutrients taken up by the palms but recycled to the soil in leaf litter, dead leaves, male inflorescence and dead roots.

(a) and (b) represent long-term soil P depletion and the sum of (a), (b) and (c) constitute the short-term requirements which the soil must be able meet annually.

Table 2.6 summarizes amounts required in the different components of the nutrient cycle.

Table 2.6 Nutrient Removal, Immobilisation and Turnover in Adult Oil Palms (kg/palm/yr)

	Nutrients			
	N	P	K	Mg
Bunch Removal	0.49	0.08	0.63	0.04
Immobilization in Palms	0.27	0.022	0.47	0.072
Nutrient Turnover in Palms	0.53	0.076	0.69	0.19
Mean Nutrient Uptake	**1.29**	**0.18**	**1.79**	**0.30**

Source: Tinker, (1976)

From the table it can be seen that the soil must be able to provide 0.18 kg P/palm/year (for palms planted at a density of 130 palms/ha with an average yield of 24 tonnes / ha/ yr) which is equivalent to 23 - 25 kg P per hectare.

2.5.7 Phosphorus in Soil Solution and Root Rhizosphere

Phosphate absorbed by plants is mostly in the orthophosphate forms ($H_2PO_4^-$ and HPO_4^{2-}) in soil solutions (Tisdale *et al.*, 1985). Rapid replenishment of the soil solution is needed to maintain this pool.

Concentrations of P in many soils of moderate P status is about 10^{-5} M (equal to 0.3 ppm) in soil solutions (Wild, 1980). Tinker (1976) suggested 3×10^{-6} M (equal to 0.03 ppm) as the absolute minimum for oil palm crops.

In the rhizosphere region chemical changes take place during the uptake of plant nutrients. The change in rhizosphere pH determines the availability of P in the root rhizosphere. Nye (1986) suggested that there were four sources of acids and bases at the rhizosphere that influence soil pH and nutrient uptake at the root/soil interface. The sources are:

a) imbalance between nutrient cation and anion uptake across the root/soil interface,

b) carbon dioxide respiration from respiration of roots and microorganisms,

c) excretion of organic acids from roots and

d) microbial production of acids from root carbon release.

On balance, Nye concluded that the imbalance between nutrient cations and anions is by far the most important factor causing pH changes in the root rhizosphere area. The rhizosphere pH changes as result of differences in uptake of cations in relation to anions and in response to P deficiency in the crops.

2.5.8 Processes Involved in the Movement of Phosphorus to Root/Soil Interface

Soluble plant nutrients reach plant roots in three ways prior to being absorbed and taken up into the plants. The mechanisms are (a) root interception, (b) movement of ions by mass movement with the soil solution and (c) diffusion of ions in the soil solution (Tisdale *et al.,* 1985). Of these 3 mechanisms, P moves to plant roots for absorption mainly via diffusion though there may be small contributions from root interception and mass flow especially in soils with high P concentrations.

When plant roots absorb phosphate ions around the roots, a diffusion gradient is set up between the roots and the outer bulk soil solution. Phosphate ions in the more highly concentrated outer areas then diffuse into the depleted zone to replace those absorbed. A rapid depletion of up to 60% of the exchangeable phosphates was observed within the root hair cylinder during the initial three days of absorption by rape and an exchangeable phosphate gradient around the root was developed to a distance of about 0.7 cm from the centre of each root (Bhat and Nye, 1973).

Hence the amount of phosphorus taken up by crops is controlled by diffusion and therefore depends highly on the diffusion coefficient of phosphates in the soil solution. Factors that affect the diffusion coefficient ultimately determine the amount of phosphorus that diffuses to the root/soil interface in readiness for plant absorption. Important factors that influence the diffusion coefficient have been discussed by Barber (1980) and include soil volumetric moisture content, the impedance factor, P buffer capacity and temperature.

2.5.9 Absorption of Phosphorus by Plant Roots

Plant roots normally absorb phosphate ions from soil solutions down to very low concentrations of phosphorus (within the range of 0.05 - 0.3 g P/ ml) (Bolan, 1981). In plant root cells and xylem sap, concentrations of P can be 100 - 1000 times more than the concentration in soil solution. This simply means that plant roots absorb P against a very steep concentration gradient, and so the uptake is active (Mengel and Kirkby, 1987). Not only is it the concentration gradient that P ions have to confront but also root cell membranes carry a nett negative charge and, because the P ions are also negatively charged, they have to move against a repelling electrical force. The whole uptake is then active and needs a lot of energy. Active absorption of phosphate ions is believed to be carried out by metabolically produced carriers which transfer the ions across membranes against steep concentration gradients (Bolan, 1991).

2.5.10 Factors Affecting P Uptake

Various plant and soil factors influence the uptake of P and have been discussed by Barber (1980). Some of the main factors are discussed below:

2.5.10.1 Change in P Absorption With Age

P absorption and uptake by plants generally declines with age. Junk and Barber (1975) observed that maximum uptake of P was 0.55 pico mole per cm per second for plants up to 28 days of age but decreased rapidly from the 28th day to 50th day to only 25%

of the rate at 28th day. This was for annual crops. For perennial crops, measured declines in P uptake rate may be due to remobilisation of P within the plants and a lower overall rate of uptake would suffice to maintain growth of new tissues and replace those removed at harvest. Bhat and Nye (1974a) reported that uptake with rape roots was active up to 8 days and then declined. There has been no work done on P uptake rate for oil palm.

2.5.10.2 Changes With Soil Depth

P uptake by oil palm, as with other crops, depends in a major way on soil conditions that affect the distribution of roots; both horizontally and vertically. P concentrations are usually high in the top 15 to 20 cm of soil due to organic matter mineralisation and fertiliser applications. P concentrations are lower at lower depths because P is less soluble and does not leach or move easily down the profile. Exceptions may occur where soils are alluvial and or where buried horizons occur to produce higher P levels at lower depths in the profile.

2.5.10.3 Morphological Properties of Roots

Nutrient uptake by plants is also influenced by root morphological characteristics. Oil palms do not have root hairs but do have quaternary roots which are responsible for the nutrient and water uptake.

Other factors that affect the uptake of P include the proportion of root system supplied with P, effect of plant P status and effect of temperature.

2.5.11 Rhizosphere Microorganisms and Phosphorus Uptake

Microorganisms play a number of very important roles in plant nutrition and they can be referred to as sources, sinks and transformers of plant nutrients. They are directly involved in decomposition and mineralisation of organic matter to release nutrients for plant uptake (2.4.2.3), and nitrogen fixation, and indirectly by causing root diseases which affect plant nutrient uptake (Darrah, 1993).

There are a large number of diverse groups of soil microorganisms living in the soil rhizosphere all depending on ATP as a source of energy. P is a very important component of ATP and therefore where P is limiting microorganisms compete directly with plants for available P in the soil solution. Microorganisms not only immobilise P but can also mineralise Po to Pi making it more available for plant uptake

Special groups of microorganisms form symbiotic relationships with plants in which the plants provide the organisms with carbon and in return phosphorus is provided to the plants. Such associations include mycorrhizae and have been reviewed by Tinker (1980 and 1984) and Bolan (1991). Mycorrhizae aid plants in P absorption from sources that are otherwise less available. The fungi are grouped into 3 groups depending on how they infect and live in plant roots; (1) ectotophicmycorrhizae, (2) ectendotrophic mycorrhizae and (3) endotrophic mycorrhizae.

Mycorrhizae aid plants in phosphorus uptake in 3 major ways; (a) absorption of phosphorus from sources unavailable to the uninfected plant, (b) alteration of plant growth to increase the root system or alter enzymes in the plant to aid absorption and (c) extension of the P depletion zone away from the roots.

The major factor influencing mycorrhizal activity is the plant P status in relation to the soil status. When there is less available P in soils for uptake, plant growth is limited by the deficiency. The plant then stimulates the growth of mycorrhizae to aid in P uptake. But when P nutrient status is improved by fertilising, the mycorrhizal activity is suppressed.

2.5.12 Summary

Soils and climate of PNG are highly suitable for oil palm cultivation. The soils have very good physical and chemical properties because they are mostly derived from volcanic ash materials. Soils are relatively young and the parent materials are mostly dacites both at Popondetta and in West New Britain.

Soil chemical tests on soils in the fertiliser trials conducted on oil palm in PNG all showed very low Olsen P (<10 mg/kg) while PR values are medium to high for Hoskins and Kapiura, very high for Bialla and low for Popondetta soils.

Field fertiliser trials in volcanic ash soils of PNG generally showed no or inconsistent responses to P fertilisers except for Bialla soils. The general lack of responses is seen despite the fact that soil P tests show very low levels of available P in the soils.

It is suggested that a soil factor or a number of different other factors are probably influencing the availability of P and its eventual uptake. This is indicated by generally low P levels (< 0.15% DM optimum) in the leaf tissues which do not change in response to P fertilisers applications.

CHAPTER 3: METHODS AND MATERIALS

3.1 SAMPLING SITES AND SAMPLING PROCEDURES

Soil samples were taken from soils developed from volcanic ash materials in the major oil palm growing areas in Papua New Guinea (PNG). The sampling sites were at Hoskins (Trial 107), Kapiura (Trial 402), Bialla (Trials 201 and 205) which are all in the Island Region and at Popondetta (Trial 323) on the Mainland.

3.1.1 Site Descriptions

A brief description of each of the sites is as follows:

3.1.1.1 Hoskins Trial 107

Soils at Hoskins are young, coarse-textured, free-draining soils developed from alluvial redeposited andesitic pumiceous sands, gravels and volcanic ash. The palms were replanted in 1983 at a density of 135 palms/hectare. Triple Superphosphate (TSP) fertiliser application at a rate of 1 kg/palm/year commenced in 1983 for the fertilised plots. The rate was increased to 2 kg/palm/year in 1985 and this continued until 1996 prior to sampling in January 1987. The control plots do not receive any P fertiliser.

3.1.1.2 Kapiura Trial 402

Soils at Kapiura are similar to those at Hoskins. Palms were planted in 1987 at a density of 120 palms/hectare from virgin forest. For fertilised plots, TSP fertilising commenced in 1990 at a rate 4 kg/palm/year.

3.1.1.3 Bialla Trials 201 and 205

Trial 201

Soils in Trial 201 are freely draining Andosols formed on intermediate to basic volcanic ash materials. Palms were planted in 1973 at a density of 115 palms/hectare. This trial is now closed and had not received any fertiliser for 3 years prior to the time of sampling.

Trial 205

The soils at this site are alluvial volcanic ash soils which are formed in materials, that have been formed elsewhere, transported and re-deposited by water. Palms at this site are newly planted and the trial only received its first application of fertilisers shortly before sampling.

3.1.1.4 Popondetta Trial 323

Soils at Popondetta are developed from alluvial volcanic ash materials that are mostly deep sandy clay loams, with good drainage and strong physical properties. At the time of sampling the site was newly replanted to oil palm and is a proposed site for a future P fertiliser trial.

3.1.2 Sampling Procedure

Soil samples at Hoskins, Kapiura and Bialla (Trial 205) were taken from control and P fertilised plots whereas at Bialla (Trial 201) and Popondetta (Trial 323) samples were taken randomly across the sites. At all sites soils were sampled at 3 depths; 0 - 10 cm, 10 - 20 cm and 20 - 30 cm. In the fertilised plots, samples were taken from within the fertilised zone which was 1m band centred at 2.5 m from the middle of the palm base. As well as sampling from the 3 depths, in Hoskins, Kapiura and Bialla (Trial 205) samples were also taken from soil pits dug by PNG Department of Agriculture and

Livestock. Horizons differentiated by horizon colour and texture were sampled seperately at each site.

Except for samples collected from the large soil pits , at each site, 5 - 7 holes were dug to 40 cm depth and using a tape measure as guide for the three depths, a handful of soil was taken with a bush knife from the different depths. From each depth at each site 4 to 5 kg of sample were collected. These soils were then air dried at room temperature for 3 to 4 days. After air drying each soil sample was mixed thoroughly and a subsample of 250 to 300 g was taken for analysis. Sampling on all sites was done in January 1997.

The samples were then brought to NZ for analysis. The soils were again air dried at 30 - 35 C in a forced air oven, crushed and sieved through a 2 mm mesh to remove plant materials and stones.

A range of New Zealand topsoil samples derived from volcanic parent materials were included in the study to provide a comparison with the soils from PNG. These soils included Taranaki (Egmont Soils) provided by Landcare and Taupo and Manawatu (Ramiha Soils) provided by Massey Soil Science Department at Massey University, all surface soils (0 - 10 cm).

Egmont soils are friable free draining soils derived from Mt. Egmont andesitic volcanic ash materials. The properties of this soil is strongly influenced by short range order minerals; allophane, imogolite and ferrihydrite (Gibbs *et al.,* 1968; McLaren and Cameron, 1996).

Taupo soils are derived from Kaharoa and Taupo rhyolitic volcanic ash materials. The soils normally have moderate PR and are sandy or gravelly, dominated by pumice or pumice-sand which have high glass content (Gibbs *et al.,* 1968; McLaren and Cameron, 1996).

Ramiha soils are mostly derived from greywacke materials and usually contain mixtures of clay minerals including kaolinite, halloysite, aluminium interlayered vermiculite and smectite. The soils are acidic with clayey and/or organic illuvial features in subsoil horizons (Gibbs *et al.*, 1968; McLaren and Cameron, 1996).

3.2 SOIL MINERAL ANALYSIS

Soil mineral analysis was performed on selected horizon samples from the profiles of Hoskins, Kapiura and Bialla (205) soils as well as 3 depths (0 - 10, 10 - 20, 20 - 30 cm) of Bialla (201) and Popondetta soils. The New Zealand soils were also included in the mineralogical analysis.

A mineral analysis procedure (NZ Soils Bureau Scientific Report Number 79 by Whitton and Churchman (1987)) was followed as outlined in Figure 3.1.

Stage 1 Removal of Calcium Carbonate

Removal of calcium carbonate is necessary to avoid interference with identification of mineral components present.

First, 10g of air dried samples were placed into 90 ml centrifuge tubes and 50 mls of distilled water was added. The samples were stirred with hand and 1 ml of bromophenol was added. Then 1:1 HCl was added dropwise until the colour changed from blue to yellow. After colour change, samples were stirred and centrifuged at 1500 rpm for 5 minutes. The supernatant liquid and any plant debris which were separated by centrifuging were then poured off leaving calcium carbonate-free soils for the next stage.

Stage 2 Removal of Organic Matter

To remove organic matter, 10 ml of distilled water and 10 ml of 30% peroxide were added to the tubes from stage 1, stirred thoroughly and then left to stand overnight to

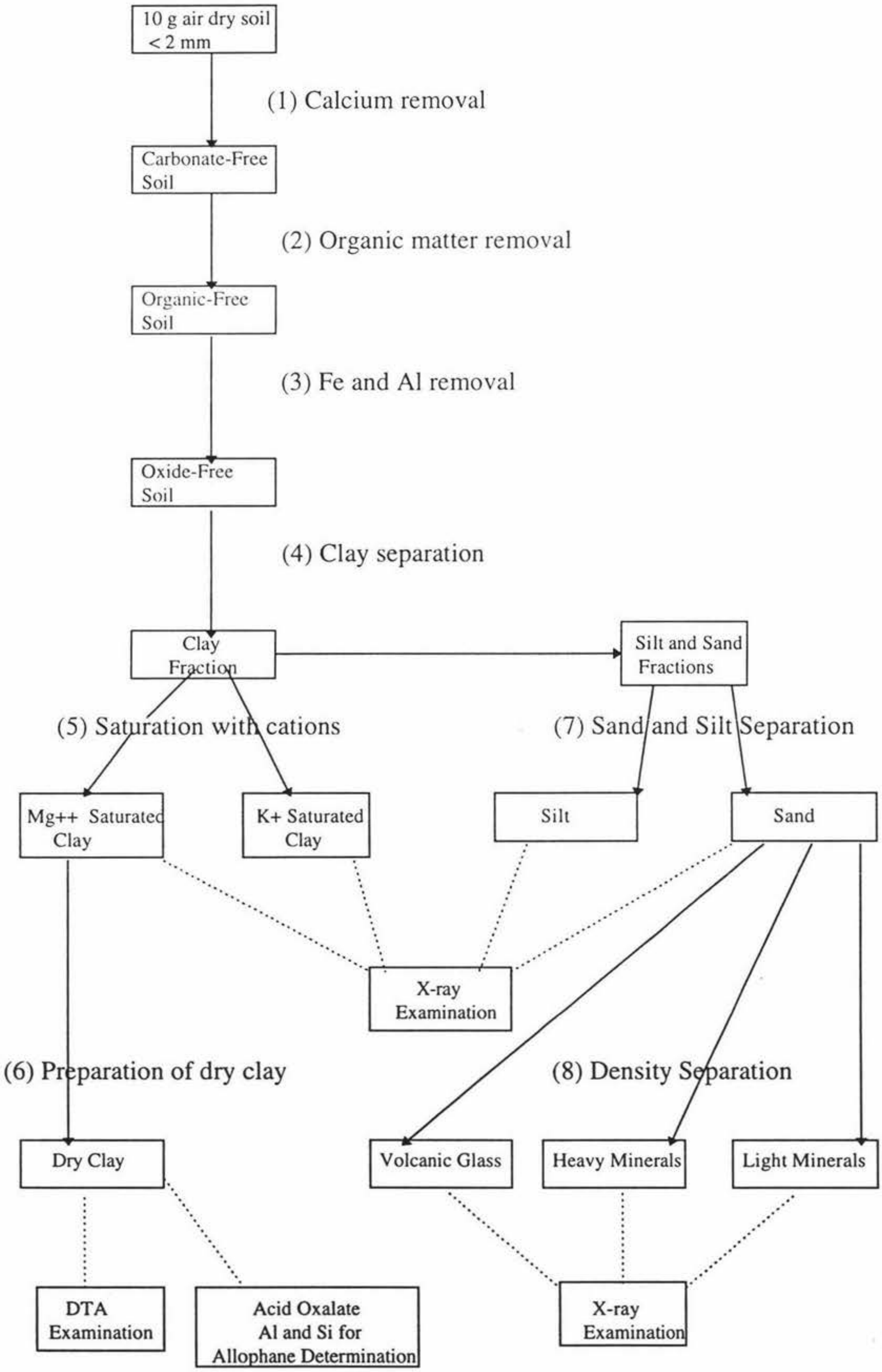


Figure 3.1 Flow sheet for mineralogical analysis of soils (Adapted from Whitton and Churchman, 1987)

allow the organic matter to be oxidised. Next day the tubes were placed into a hot water bath for oxidation at higher temperature (90 - 100 C). While the tubes were in the hot water bath they were stirred occasionally until frothing stopped. When frothing stopped the samples were removed, stirred and centrifuged at 1500 rpm for 15 minutes. The supernatant was then decanted. The samples were then ready for the next stage.

Stage 3 Removal of Iron (Fe) and Aluminum (Al) Oxides

To remove Fe and Al oxides and hydroxides from the organic matter free soils, 30 ml of 0.25M citrate reagent (75 g $C_3H_4(OH).(COONa)_3.2H_2O$ dissolved in 1 litre of water and pH adjusted to 7.3 with saturated citric acid solution) and 5 ml of 1M sodium bicarbonate were added to the tubes. After stirring, the tubes were placed in a hot water bath at a temperature of 90 - 100 C. When the solutions were hot, they were stirred and 1 g of sodium dithionite was added to each tube while gently stirring. The tubes were then left in the bath for a further 15 minutes, stirring at 5 minutes intervals. After this, samples were centrifuged at 1500 rpm for 5 minutes and the supernatant was discarded.

For samples with high iron oxide contents, the procedure was repeated until the reddish-brownish colour disappeared. Finally the samples were rinsed with 30 ml of citrate reagent, heated in the hot water bath, centrifuged, and the supernatant discarded leaving oxide-free soils.

Stage 4 Separation of Samples into Clay, Silt and Sand Fractions

Clay Separation

Distilled water was added to the tubes and the contents were mixed with the help of a mechanical stirrer. The tubes were centrifuged at 1000 rpm for 5 minutes and the supernatant clay suspension was poured into a 1 litre beaker. This was repeated 4 to 5 times reducing the centrifuge time to 3 minutes and the speed to 800 rpm until the supernatant was clear. The remaining residue in the tubes comprised the sand and silt fractions.

Stage 5 Saturation with Cations

About 10 ml aliquots of clay suspension were transferred to 15 ml tubes and saturated with 3 ml of 1M KCl. The clay was then allowed to flocculate, under gravity overnight. The next day the clear supernatant was sucked off and 10 ml of KCl added and the tubes were shaken and left to flocculate again overnight. Then the clear supernatant was sucked off, distilled water was added and the tubes were centrifuged at 1500 rpm for 15 minutes. After centrifuging, the clear supernatant was poured away. The additional distilled water and centrifuging steps were repeated until the clay began to disperse. X-ray slides were then prepared. To prepare x-ray slides, clean dry glasses were covered with 1 - 2 ml of clay suspension and were allowed to air dry. Then using the x-ray diffractometer, the samples were analysed for chlorites.

To the remaining bulk clay suspension, 10 ml of $MgCl_2$ was added followed by 1 drop of bromophenol blue indicator. Then 1:1 HCl was added dropwise until the colour turned yellow. The beaker was then filled with distilled water and left overnight to flocculate. The clear supernatant was then sucked off, distilled water was added and was left to flocculate overnight again. The supernatant was then sucked off again and the Mg^{++} saturated clays were prepared for X-ray slide viewing. In fact, 2 batches of x-ray slides were prepared. One batch was sprayed with glycerol. Using an x-ray diffractometer, the sprayed slides were analysed for 2:1 clay minerals. Unsprayed slides were analysed for quartz, feldspars and other ferromagnesan minerals.

Stage 6 Preparation of Dry Clay

After slides of Mg^{++}-saturated clays had been prepared, the remaining suspensions in the tubes were air dried in petri dishes, finely ground and stored in vials. Slides were prepared and analysed for kandites and gibbsite by Differential Thermal Analysis (DTA).

Dried samples from here were also analysed for allophane using an acid oxalate extraction procedure (Blakemore *et al.*, 1987).

Stage 7 Sand and Silt Separation

After clay separation, the remaining sand and silt residues were dispersed with distilled water, stirred and left to stand for 5 minutes. The suspension containing silt was poured into another beaker and the process was repeated until the suspension stayed clear. The suspension was then left to settle overnight and the supernatant liquid was sucked off the next day. The silt was then washed with distilled water and air dried.

From the silt fraction, X-ray slides were prepared and analysed for glass and ferromagnesan minerals. Slides were also prepared and analysed for kandite by DTA.

The sand fraction, which was the residue after silt separation, was oven dried overnight and stored in vials for separation into heavy and light minerals as discussed below.

Stage 8 Separation of Sand Fraction for Heavy and Light Mineral Analysis

The oven-dried sand fractions were separated into light and heavy minerals by using sodium polytungstate (SPT). To do this, 0.5 g of sand was placed in a 10 ml centrifuge tube and 5 ml SPT (density $2.45 g.cm^{-3}$) was added. The contents were then stirred to suspend sand grains and break up any aggregates. After stirring, the tubes were allowed to settle. Then a glass rod with a button at the end was pushed slowly into the tube through the light minerals separating them from heavy minerals. Slowly the floating light minerals (volcanic glass and plant opals) were poured into a filter paper and collected. This procedure was repeated using SPT of $2.8 g.cm^{-3}$ density and this time the heavy minerals which sank to the bottom were collected. Both light and heavy minerals were then oven dried at 110 C and stored in vials for x-ray and optical examinations. The light minerals were then analysed by XRD for volcanic glass, plant opals, feldspars and quartz while heavy minerals were analysed for heavy ferromagnesan minerals.

3.2.1 Determination of Non-crystalline Secondary Minerals (Allophane and Ferrihydrite)

For determination of non-crystalline secondary minerals, aluminum, iron and silicon were extracted with acid ammonium oxalate and sodium pyrophosphate using the procedure of Blakemore *et al.*, (1987).

3.2.1.1 Acid Oxalate Extract.

Acid ammonium oxalate extracts Al, Fe and Si from noncrystalline minerals as well as from complexes formed with organic matter.(Parfitt and Hemni, 1982)

A gram of soil (air dried, <2 mm) was weighed into 250 ml centrifuge bottles and 100 ml of acid oxalate (81 g ammonium oxalate with 54 g oxalic acid dissolved in water and made up to 5 litres at pH of 3) was added. The bottles were then shaken end-over-end for 4 hours in the dark. After shaking, the samples were filtered through Whatman Filter Paper No. 42 and about 10 ml of the filtrate was collected.

Then 1 ml of the filtrate was diluted with 9 ml of diluent solution (1.41 g CsCl and 22 ml conc. HCl made up to 1 litre with water) and Al, Fe and Si were determined using Atomic Absorption Spectrometry (AAS).

3.2.1.2 Sodium Pyrophosphate Extraction

Sodium Pyrophosphate extracts Al and Fe from complexes with organic matter only.

A gram of soil (air dried, <2 mm) was weighed into a 250 ml centrifuge bottle and 100 ml of sodium pyrophosphate was added. The tubes were then shaken end-over-end for 16 hours in the dark. After shaking, 5 drops of 0.2% Superfloc was added and the bottles were shaken vigorously and centrifuged for 1 hour at 1500 rpm. After centrifuging, 1 ml of the extract was diluted with 4 ml of distilled water and Al and Fe were determined using AAS.

3.3 SOIL CHEMICAL ANALYSIS

Soil samples were analysed for pH in water, 1M KCl, 1M NaF and for phosphate retention (PR) using procedures according to Blakemore *et al.,* (1987). For all chemical analyses, samples were analysed in duplicate. Soils samples labelled with NP (e.g. 107NP) are from nonfertilised plots while with HP (e.g. 107HP) are from fertilised plots.

3.3.1 pH in Water

To measure pH in water, 10g of air dried soil (<2 mm) was weighed into a small 50 ml plastic cups. Then 25 ml of distilled water was added and the samples were stirred and left to stand overnight. Without stirring the next day, pH was read on a PHM82 Standard pH meter.

3.3.2 pH in 1M KCl

pH in 1M KCl measures absolute acidity in a soil. The K^+ ions displace H^+ ions from the minerals surfaces and these are measured to determine the soil acidity.

The same procedure as for pH determination in water was followed except 1M KCl was used instead of water.

3.3.3 pH in 1M NaF

pH measurement in 1M NaF determines the presence of mainly active aluminum hydroxides in the soils (Fieldes and Perrot, 1966). The fluoride ions displace hydroxyl ions from mineral surfaces by complexing with associated Al.

A gram of air dried soil (<2 mm) was weighed into 100 ml plastic cups and 50 mls of 1M NaF reagent was added. The mixture was then stirred vigorously for 1 minute and a minute later pH was read using the pH meter.

3.3.4 Phosphate Retention

To measure PR, 5.0 g samples of soil (air dried,< 2 mm) were weighed into 50 ml polypropylene centrifuge tubes. Then 25 ml of 1000 ppm P solution (KH_2PO_4) was added and tubes were shaken end-over-end at 50 rpm, overnight. After shaking, the tubes were centrifuged at 8000 rpm for 5 minutes and 2 ml of supernatant was pipetted into 50 ml volumetric flasks. Then 12.5 ml of nitric-vanomolybdate reagent was added and the volume was then made to 50 ml with distilled water (Blakemore *et al.,* 1987). Flasks were shaken and left to stand for 30 minutes to develop colour. After colour development, absorbance readings were made using an UV spectrophotometer at a wavelength of 420 nm. Standards and blank were also prepared and measured accordingly.

3.4 PHOSPHORUS FRACTIONATION

Two phosphorus fractionation procedures were carried out to identify the forms of P present in the soils. The methods used were the sequential extraction of Hedley *et al.,* (1994) and the bicarbonate fractionation of Bowman and Cole (1978b).

3.4.1 Sequential Extraction Procedure

This procedure is outlined in the flow chart in Figure 3.2.

Stage 1 Resin-Pi

In this procedure 0.5g of sieved soil (<2 mm) was weighed into 50 ml polypropylene centrifuge tubes and 30 ml of distilled water was added. Then an anion (0.19 - 0.2 meq. of charge) and a cation (0.24 - 0.26 meq. of charge) resin strip was placed into each tube. Tubes were then shaken end-over-end at 50 rpm for 16 hours at 25 C. After shaking for 16 hours, the strips were removed from the tubes, rinsed with distilled water and transferred to another set of 50 ml polypropylene centrifuge tubes. Then 30 ml of 0.5M NaCl was added and the tubes were shaken end-over-end for 2 hours.

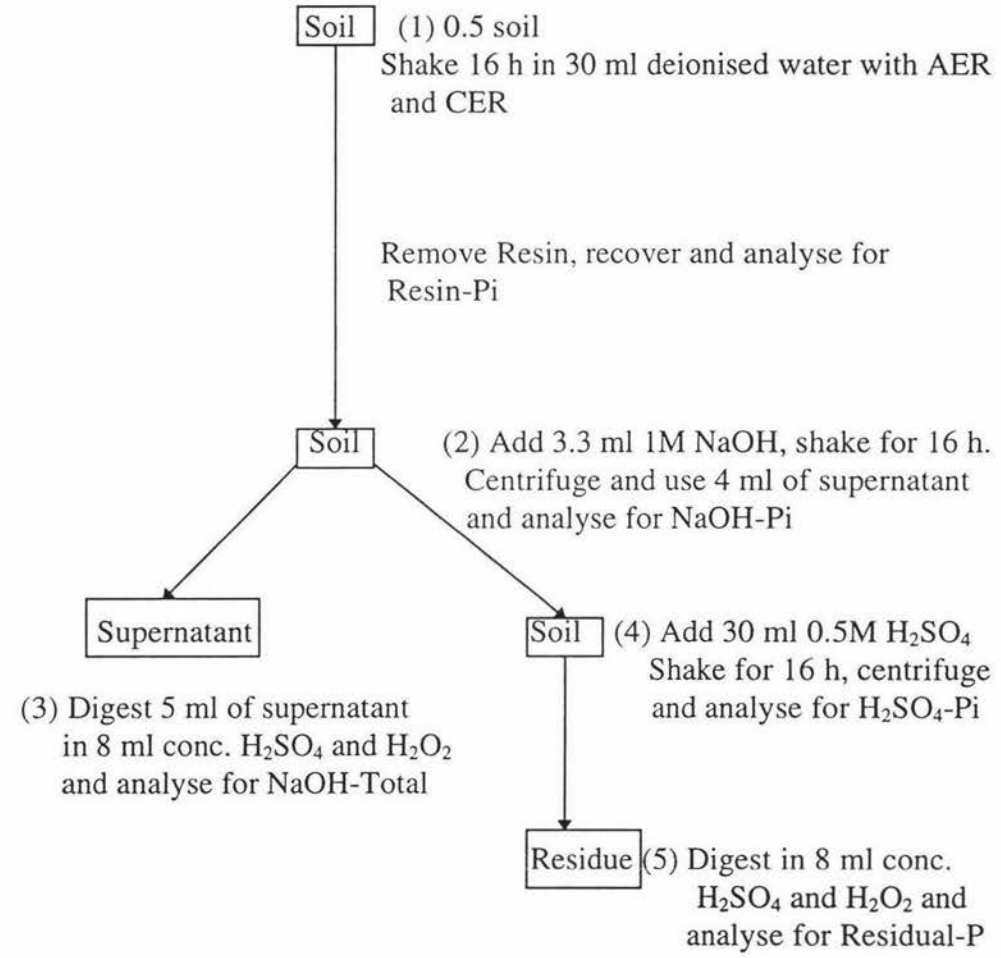


Figure 3.2 Outline of Hedley's Sequential P Fractionation Procedure

After shaking, 4 ml of the solution was pipetted into a 50 ml volumetric flask. Then 32 ml of distilled water was added followed by 10 ml of Murphy and Riley solution (Murphy and Riley, 1962) and the volume was made up to 50 ml. The flasks were then shaken and left to stand for 30 minutes to develop maximum colour, after which, P was determined using a UV spectrophotometer at 712 nm wavelength.

Stage 2 NaOH-Pi

To the soil suspension left after removal of resin strips, 3.3 cm^3 of 1M NaOH was added. The tubes were then shaken end-over-end for another 16 hours. After shaking, tubes were centrifuged at 8000 rpm for 5 minutes and 4 ml of the extract was carefully taken to develop colour with Murphy and Riley reagent. P was determined as was done for the Resin-Pi determination. The P determined in this step was termed NaOH-Pi.

Stage 3 NaOH-Po

From the extracts used for the determination of NaOH-Pi in stage 2, 5 ml was pipetted into 50 ml conical flasks. Then 8 ml of concentrated H_2SO_4 acid was added to each of the flasks which were then covered with glass filter funnels (to stop loss through evaporation) and heated on a hot plate. The temperature was slowly increased to
300 C for 2 hours. After 2 hours of heating, the flasks were cooled, 0.5 ml of H_2O_2 was added to each and then they were heated for 30 minutes until the contents were clear. They were then cooled and samples were transferred into 100 ml digest tubes by washing with deionised water. Volumes were made to 50 ml with distilled water and the contents were thoroughly mixed on a vortex mixer.

Because the samples were very acidic, they were neutralised before P was determined. To neutralise, 1 ml of the extract was pipetted into a 50 ml volumetric flask and 3 drops of p-nitrophenol indicator were added. This was followed by addition of 4M NaOH dropwise while swirling until the colour turned yellow. Then 0.5M H_2SO_4 was added dropwise while swirling until the solution became clear again. Then P was determined using the same procedure as for Resin-Pi determination. P determined here is referred to as total NaOH-P and the difference between this fraction and NaOH-Pi is a measure of NaOH-Po.

Stage 4 H_2SO_4-Pi

The supernatant remaining after extraction of NaOH-Pi was carefully poured away and the residue was then used. In each of the tubes, 30 ml of 0.5M H_2SO_4 was added and tubes were shaken for 16 hours as was done in stage 2. After shaking, the samples were centrifuged at 8000 rpm for 5 minutes. Then 1 ml of the aliquot was pippeted into 50 ml volumetric flasks and neutralised before colour development with Murphy and Riley solution. P then was determined and this fraction is referred to as H_2SO_4-Pi.

Stage 5 Residual-P

The remaining supernatant after H_2SO_4-Pi determination was carefully poured away and similar procedure to stage 3 was followed with the soil residues. P determined here is termed Residual-P.

3.4.2 Bicarbonate P Fractionation

In this procedure inorganic (bicarbonate Pi) and organic (bicarbonate - Po) forms of P were determined following bicarbonate extraction using the Olsen P method (Bowman and Cole, 1978b). 1 g of soil (air dried ,<2 mm) was weighed into 50 ml polypropylene centrifuge tubes. Then 20 ml of 0.5M sodium bicarbonate solution at pH 8.5 was added and the tubes were shaken end-over-end at 50 rpm for 30 minutes. After shaking, samples were centrifuged at 9000 rpm for 1 minute and then filtered through Whatman No 6. filter paper by suction, using a water pump. The filtrate was collected and analysed as follows.

3.4.2.1 Bicarbonate Pi

4 ml of the filtrate was pipetted into a 50 ml volumetric flask along with 32 ml of distilled water. Then 10 ml of Murphy and Riley solution was added and the volume made up to 50 ml with distilled water. P was then determined as in section 3.4.1 stage 1. The P determined here is referred to as Bicarb.-Pi.

3.4.2.2 Bicarbonate Po

10 ml of the remaining bicarbonate extract filtrate was pipetted into digestion tubes. Then 1 ml of concentrated H_2SO_4 acid and 0.3 g of ammonium persulphate were added. The tubes were then heated in an aluminum block for 30 minutes gradually

increasing the temperature to 150 C. After heating, the tubes were cooled, volumes made up to 50 ml with distilled water and contents thoroughly mixed on a vortex mixer. Then 10 ml of this digest was neutralised and P was determined as in section 3.4.1 Stage 3. P determined is referred to as total bicarbonate-P and the difference between this and Bicarb.-Pi was the Bicarb.- Po.

3.5 TOTAL CARBON AND NITROGEN DETERMINATION

Total carbon and nitrogen were determined by Landcare Research. The samples were analysed on a LECO CNS - 2000 analyser by combustion with ultrapure oxygen at 1050 C. Carbon dioxide produced was measured by an Infrared Detector and N by a Thermal Conductivity detector. Both detectors were calibrated using a standard EDTA.

3.6 OVEN DRY WEIGHT

In order to correct all the results to dry weight basis, oven dry weight was determined for each soil. Between 10 and 20 g of soil was weighed and oven dried for 24 hours at 105 C. After drying the samples were removed from the oven and weights were recorded immediately. The difference in weight was calculated and used to adjust all data to oven dry weight basis.

CHAPTER 4: RESULTS AND DISCUSSION

4.1 SOIL MINERALS

In this section special attention is paid to soil minerals that are of relevance to the chemistry of phosphorus in volcanic ash soils. Minerals in the sand, silt and clay fractions and acid oxalate and sodium pyrophosphate extracts of Al, Fe and Si from whole soils are discussed.

The sand and silt fractions consist mostly of minerals derived directly from the parent materials and therefore are discussed together. By contrast secondary clay minerals are altered weathered products which can differ markedly from those found in the parent materials and therefore their findings are discussed separately.

4.1.1 Sand and Silt Fractions

Volcanic glass in the Hoskins and Kapiura soils is high to very high at all soil depths and in both sand and silt fractions, as shown in Table 4.1. In soils from Bialla the occurrence of volcanic glass is moderate in the sand fraction but very high in the silt fraction. By contrast volcanic glass in the Popondetta soils is very low to low in the sand fraction but very high in the silt fraction with plant opals occurring at all depths.

The three New Zealand soils have low volcanic glass in the sand fraction. Egmont and Taupo soils have large amounts of volcanic glass in the silt fraction but the Ramiha soil has none.

Volcanic glasses are the least resistant to chemical weathering of all common primary volcanic minerals (Shoji, 1986) and they are regarded as the main source of secondary minerals in soils of PNG and elsewhere (Shoji *et al.,* 1975). The chemical composition and bonding characteristics of volcanic glass determines the composition and characteristics of secondary minerals such as allophane (Kirkman and McHardy, 1980).

The presence of high levels of volcanic glass in these oil palm growing soils indicates their relatively young age.

Moderate levels of kandites (kaolinites and halloysites) are present in the silt fractions in Hoskins, Kapiura and Bialla (205) soils at the lower depths but none are found in the Popondetta soils.

Plant opals in the silt fraction were only seen in soils from Popondetta in this study. No plant opals were found in soils from the Island region although Parfitt (1975) reported their presence in some Hoskins soils. According to Parfitt (1974) and Dahlgren *et al.*, (1993) plant opals are mostly present in top soils of very recent volcanic ash soil and mostly in the silt fraction. There are two possible reasons for plant opal formation. Firstly organic matter forms complexes with Al ions which renders them unavailable to form other secondary minerals in association with silica. Excess silica then precipitates within the cells of plants and microorganisms cells to form opals. Secondly when the composition of silica in relation to other cations is high in the parent materials, excess silica in the soils then form opals as discussed above. It is this form of evidence that leads to the suggestion that the Popondetta soils are probably somewhere between dacites and andesites. Due to weathering, silica released from volcanic glass accumulates in plants and microorganism cells and precipitates on cell walls producing shapes which are related to the original cells (Parfitt, 1975).

The presence of kandites at lower depths in Hoskins soil profile indicates the possible existence of buried soil horizons. This was also reported by Bleeker and Parffit (1974) for soils in the Cape Hoskins area. Also the fact that there has been a sequence of volcanic eruptions in the region over the last 2000 years adds weight to the hypothesis that soils have developed and then been buried by subsequent ashes.

Table 4.1 Sand and Silt Fractions Minerals in a Range of Volcanic Soils from PNG and NZ

		Sand Fractions	Silt Fraction	
Sample	Depth (cm)	Volcanic Glass/Plant Opals	Kandites	Volcanic Glass
Hoskins	0 - 15	*****		*****
(107)	15 - 35	*****		*****
	35 - 70	*****		*****
	70 - 100	****	***	*****
	100 - 175	*****	***	*****
	175 - 200	*****		*****
Kapiura	0 - 10	****		*****
(402)	10 - 23	*****		*****
	23 - 45	*****	***	*****
	45 - 70	*****	**	*****
	70 - 105	*****	*	*****
	105 - 133	*****	Mostly	*****
	133 - 200	*****	glass	*****
Bialla	0 - 15	***		*****
(205)	15 - 40	***		*****
	40 - 70	***		*****
	70 -170	***	***	*****
	170 - 200	****	***	*****
(201)	0 - 10	***		*****
	10 - 20	***		*****
	20 - 30	***		*****
Popondetta	0 - 10	**	HB	***** #
(323)	10 - 20	* #	HB	***** #
	20 - 30	*	HB	***** #
Egmont	0 - 10	**		*****
Taupo	0 - 10	**		*****
Ramiha	0 - 10	**		

Plant opals present

* = 0 - 5 % very low, ** = 5 - 10% low , *** = 10 - 25% moderate, **** = 25 - 50% high, ***** = >50% very high

HB = Hornblende, Note here that hornblende is not a kandite

Volcanic glass in Popondetta had yellow-orange colour due to iron coatings indicating highly weathered materials.

Volcanic glass in WNB soils were rhyolitic, clear and smaller in structure than Taupo materials.

The primary spectra of soil minerals (Appendix 6) and heavy minerals (Appendix 7) in the Hoskins, Kapiura and Bialla soils are similar indicating that they all are probably derived from parent materials of similar chemical composition. Differences in the secondary minerals probably arise from differences in age. This means that the age of the soil varies at the three different locations in the Island Region.

Soils at Popondetta are quite different from those of the other areas as can be seen by the presence of high amounts of hornblende and absence of augite and hypersthene in the heavy mineral fraction (Appendix 7). High amounts of hornblende in volcanic ash materials from Mt. Lamington (near Popondetta) were also reported by Ruxton (1966).

In general the mineralogy of these PNG soils shows that the soils are developed from dacitic parent materials and are relatively young. There is also some evidence of buried horizons as shown by the presence of kandites at the lower depths in the Hoskins soil profile.

4.1.2 Clay Fraction

Common clay minerals in all the soils include volcanic glass, allophane and kandites (Table 4.2). These minerals occur from low to very high amounts. Minor minerals include feldspars, cristobolite, quartz and hydroxy interlayered vermiculite. The clay mineral analysis fractions are summarised in Table 4.2.

High to very high abundances of volcanic glass in all soils again indicates the relatively young age of these volcanic soils; too young for the glass to weather away even in the clay fraction.

Allophane in both Hoskins and Kapiura soils is high in the surface (35 - 45 cm) horizons but decreases to low or very low levels at lower depths. Kandites on the other hand are low to very low in the surface but increase at lower depths.

The high levels of allophane in soil surface layers indicates rapid weathering in these zones as compared to lower depths, while the presence of kandites in sand and silt fractions at lower depths is interpreted as further evidence for older buried subsurface horizons. However halloysite which is a kandite can form at lower depths due to enrichment of silica leached down from surface layers. Halloysite has been reported to form directly from volcanic ash materials where silica concentrations are high in relation to Al and in soils with poor drainage (Parfitt *et al.*, 1984, Bleeker and Parfitt, 1974 and Kirkman and McHardy, 1980) so this may offer an alternative explanation to the buried horizon hypothesis.

For soils at Bialla Trials (201 and 205), allophane content is relatively high at all depths. These Bialla soils appear to be more weathered by comparison with those at Hoskins, Kapiura and Popondetta. With increasing age the amount of secondary clay minerals in the volcanic ash soils generally increases as the primary minerals, mostly glass, are weathered and transformed into clay minerals (Lowe, 1986). Studies in volcanic ash soils in New Zealand have shown that tephras younger than 3000 years have less than 5% clay; 10,000 to 50,000 year-old tephras have 15 - 30% clay and those greater than 50,000 years have greater than 60% clay (Lowe, 1986).

The presence of high amounts of allophane at all soil depths in Trial 205, at Bialla, is probably due to the fact that the soils are of alluvial origin and the parent materials have been transported to their present location at a more recent date. Hence the allophane has been formed at some other location.

Table 4.2 Clay Fraction Minerals

Sample	Depth (cm)	Allophane	Kandites	Volcanic Glass	Others
Hoskins (107)	0 - 15	****	*	*****	F,Cr,HIV
	15 - 35	***		*****	F,Cr,HIV
	35 - 70	*	*****	****	F,Cr,HIV
	70 - 100	*	*****	****	F,Cr,HIV
	100 - 175	**	****	****	F,Cr,HIV
	175 - 200	**	****	****	F,Cr,HIV
Kapiura (402)	0 - 10	****	**	****	F,Cr,HIV
	10 - 23	****	**	****	F,Cr,HIV
	23 - 45	***	****	****	F,Cr,HIV
	45 - 70	*	*****	***	F,Cr,HIV
	70 - 105	*	*****	****	F,Cr,HIV
	105 - 133	*	*****	****	F,Cr,HIV
	133 - 200	*	****	*****	F,Cr,HIV
Bialla (205)	0 - 15	****	*	*****	F,Cr,HIV
	15 - 40	****		*****	F,Cr,HIV
	40 - 70	****		****	F,Cr,HIV
	70 -170	****	**	*****	F,Cr,HIV
	170 - 200	***	***	*****	F,Cr,HIV
(201)	0 - 10	****	*	****	F,Cr,HIV
	10 - 20	****		****	F,Cr,HIV
	20 - 30	****		****	F,Cr,HIV

Table 4.2 continued

Sample	Depth (cm)	Allophane	Kandites	Volcanic Glass	Others
Popondetta (323)	0 - 10	*	****	*****	F,Cr, HIV Q
	10 - 20	*	****	****	F,Cr,HIV Q
	20 - 30	*	****	****	F,Cr,HIV Q
Egmont	0 - 10	****	***	****	F, Cr,HIV Q, M, V
Taupo	0 - 10	***		*****	F,Cr,HIV Q
Ramiha	0 - 10	*	***		F, Cr, HIV Q,M,V

* = 0 - 5 % very low
** = 5 - 10% low
*** = 10 - 25% moderate
**** = 25 - 50% high
***** = >50% very high

F = Feldspars, Cr = Cristobolite, Q = Quartz, HIV = Hydroxy Interlayered Vermiculites, M = Micas and V = Vermiculites.

For Popondetta soils, allophane content is very low whereas kandite levels are high. The soils here are developed from mixed, volcanic, alluvial materials. Bleeker (1987) reported high PR due to high levels of allophane at other locations but this was not apparent in this area. The small amounts of allophane found in this study may be due to the fact that the volcanic ash materials are from a very recent origin (1951) and therefore time has not been sufficient for weathering and mineral transformations to occur. Also surface soil which probably was well-weathered, was removed by bulldozers during preparation of the site prior to the second planting.

4.1.3 Non-crystalline Secondary Soil Minerals

Acid-oxalate extracts aluminum (Al_o), iron (Fe_o) and silicon (Si_o) from both amorphous soil minerals and organic matter whereas pyrophosphate extracts only aluminum (Al_p) and iron (Fe_p) from organic forms. The difference between the two is taken to represent Al and Fe extracted from the amorphous soil minerals.

The atomic ratio of Al (Al_o - Al_p) from amorphous minerals to Si_o is determined and is multiplied by an appropriate factor (which varies with the ratio) to determine the allophane content (Parfitt, 1990). Ferrihydrite is determined by multiplying Fe_o by 1.7 (Parfitt and Wilson, 1985).

Parfitt and Wilson (1985) cautioned that this method of allophane and ferrihydrite determination only gives an approximate estimate for the following reasons:

1. Some imogolite and ferrihydrite will be dissolved by the acid oxalate in addition to humus Al, Fe complexes

2. Acid-oxalate possibly dissolves Al from some chlorite and disordered gibbsites (but this is not likely to be a significant problem in this study because the soils contain mostly volcanic glass minerals)

3. Pyrophosphate can disperse iron oxides and clay minerals

Therefore careful interpretation of the data is recommended.

Results for individual soils are as follows:

4.1.3.1 Hoskins Soils (107)

The higher levels of Al_o and Fe_o at 0 - 15 cm depth relative to lower levels in the subsoils (70 - 150 cm) is probably due to greater weathering of soil minerals at the surface horizons (Table 4.3). However the elevated level of these oxalate fractions at the 100 - 175 cm depth was not expected and is somewhat anomalous. This finding, along with other evidence, did raise the possibility of the occurrence of a buried soil horizon in the Hoskins soil profile, and this hypothesis is advanced in section 4.5.

A high Al/Si atomic ratios (Table 4.3) in the surface soils (around 2:1) suggests intense weathering and leaching of silica ions may be occurring in these soils with consequent movement of Si to lower depths. Rainfall and drainage seem to have a major influence on clay formation because of their influence on the Al/Si ratio. Parfitt *et al.*, (1983) studying NZ soils reported that high rainfall increased the Al/Si ratio to 2:1 and favoured the formation of imogolite and allophane whereas low rainfall lowered the Al/Si ratio to 1:1 and favoured the formation of high-silica allophane and halloysite.

4.1.3.2 Kapiura Soils (402)

For Kapiura soils Al_o and Fe_o were high at the surface but decreased with increasing depth (Table 4.3).

A high Al/Si atomic ratio at 0 - 10 cm depth (around 2:1) indicates intense weathering and presence of high levels of amorphous minerals.

4.1.3.3 Bialla Soils (205 and 201)

For Bialla soils, Al_o is very high (3%) and increases with depth to more than 5% (Table 4.3). Also Fe_o is high and increases to very high levels (> 2%) at lower depths. This pattern is unrelated to weathering stage because of the alluvial nature of these soils which has over-ridden natural in-situ weathering processes.

Table 4.3 Acid Oxalate Al, Fe and Si Extracts

Soil Site	Sample	Depth (cm)	Alo %	Feo%	Al/Si Ratio	Ferrihydrite %	Allophane %	P Retention %
Hoskins	107NP	0 - 10	1.33	0.6	2.04	1	4	62
	107HP	0 - 10	1.48	0.66	1.98	1	4	68
	107 Profile	0 - 15	1.91	0.73	2.16	1	5	73
		15 - 35	0.64	0.27	1.62	0.5	2	35
		35 - 70	0.5	0.86	2.17	1	2	44
		70 - 100	1.09	0.92	1.52	2	4	59
		100 - 175	1.36	1.37	1.66	2	5	69
		175 - 200	0.58	0.35	2.20	0.6	2	32
Kapiura	402NP	0 - 10	0.99	0.67	2.01	1	2	62
	402HP	0 - 10	1.18	0.69	2.25	1	3	61
	402Profile	0 - 10	1.57	0.79	2.14	1	4	66
		10 - 23	2.25	0.88	1.92	2	8	53
		23 - 45	1.24	0.58	1.52	1	5	54
		45 - 70	0.16	0.3	2.08	0.5	1	27
		70 - 105	0.03	0.09	1.04	0.2	0.2	12
		105 - 133	0.02	0.04	0	0.1	0	12
		133 - 200	0.06	0.04	0	0.1	0	8
Bialla	205NP	0 - 10	2.75	1.34	1.91	2	9	87
	205HP	0 - 10	2.77	1.41	1.91	2	9	93
	205 Profile	0 - 15	3.02	1.5	1.84	3	10	90
		15 - 40	4.42	1.85	1.67	3	19	97
		40 - 70	6.23	2.22	1.71	4	27	97
		70 - 170	6.79	2.36	1.74	4	29	97
		170 - 200	5.96	1.94	1.85	3	24	95
Bialla	201	0 - 10	3.15	1.37	1.93	2	10	94
		10 - 20	3.6	1.43	2.03	2	12	95
		20 - 30	3.37	1.21	1.83	2	13	94
Popondetta	323	0 - 10	0.26	0.45	1.56	0.8	0.4	31
		10 - 20	0.25	0.45	2.78	0.8	0.4	31
		20 - 30	0.28	0.44	1.62	0.8	0.5	33
NZ Soils	Egmont	0 - 10	2.43	0.72	2.47	1	9	69
	Taupo	0 - 10	1.1	0.34	2.68	0.6	3	55
	Ramiha	0 - 10	0.94	0.94	2.71	0.3	1	65

The relatively low Al_o values of topsoils as compared to lower depths is probably due to one of two reasons;

(a) Al ions forming complexes with organic matter in topsoils and therefore not being available to form amorphous minerals, and/or

(b) horizons at lower depths are probably more weathered and of greater age than the surface soils.

Calculated allophane and ferrihydrite contents as a result of generally very high Al_o and Fe_o levels in Bialla soils are very high by comparison with the other soils. High allophane levels, as determined by calculations here correlate well with the clay fraction results (Table 4.2).

4.1.3.4 Popondetta Soils (323)

For soils in Popondetta, low Al_o and Fe_o levels were found. This coincides with very low allophane and ferrihydrite minerals by comparison with soils in the Island Region (Table 4.3). The relatively low Al_o and Fe_o contents in the Popondetta compared to the others in this study are probably due to the fact that the parent materials are from a recent (1951) eruption, and the soils are relatively young and unweathered.

4.1.3.5 New Zealand Soils

Egmont and Taupo soils results are as expected. Egmont, developed from andesitic ash materials, has a relatively high Al_o value of 2.43% which was higher than most PNG soils except for Bialla soils (Table 4.3). The Ramiha soil which which has less volcanic influence has a very low Al_o (0.94%) content. Taupo, is only slightly higher than Ramiha, similar to Kapiura and less than Hoskins and Bialla soils. However allophane content calculated in Table 4.3 is much lower than that shown in Table 4.2 because Table 4.2 is only for clay fractions while Table 4.3 is from whole soils.

4.2 SOIL CHEMICAL PROPERTIES

Soil chemical properties discussed in this section include pH in water (1:2.5) ($pH_{(H_2O)}$), 1M KCl ($pH_{(KCl)}$), 1M NaF ($pH_{(NaF)}$) and PR. No statistical treatment of data for correlationship between the soil chemical properties was done because the results were not normally distributed.

4.2.1 pH in Water and 1M KCl

For Hoskins, Kapiura and Bialla soils, all in the Island Region, $pH_{(H_2O)}$ ranges from 5.9 to 6.6 being slightly acid for all three depths (Table 4.4). The $pH_{(H_2O)}$ for Popondetta soils is lower than the Island Region soils and ranges from 5.3 to 6.3, making the soils here moderately to slightly acidic.

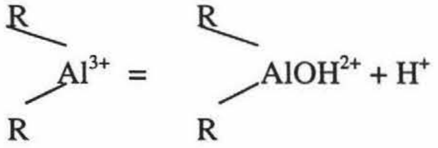
The negative ΔpH ($\Delta pH = pH_{(KCl)} - pH_{(H_2O)}$) indicates the presence of predominantly negatively charged minerals in the soils or at least a nett negative overall charge. The sign and magnitude of ΔpH relates to the sign and magnitude of the soil mineral surface charge (Uehara and Gillman, 1981). $pH_{(H_2O)}$ is usually higher than $pH_{(KCl)}$ for soils with a net negatively charged mineral surfaces.

$pH_{(KCl}$ measures the reserve acidity and is a measure of the following forms of acidity (McBride, 1994);

1) organic acids that release H^+ by dissociation;

$$R\text{-}H = R^- + H^+$$

2) Al^{3+} - organic complexes that release acidity by hydrolysis, eg:



3) exchangeable H^+ and Al^{3+}, released by cation exchange or by hydrolysis, e.g.:

$$K^+ + H^+\text{-clay mineral} = H^+ + K^+\text{-clay mineral} \quad \text{(exchange)}$$

$$K^+ + Al^{3+}\text{-clay mineral} = AlOH^{2+} + K^+\text{-clay mineral} + H^+ \quad \text{(hydrolysis)}$$

4) nonexchangeable forms of acidity on minerals:

$$>\text{Fe-OH}_2]^{+1/2} = >\text{Fe-OH}]^{-1/2} + H^+$$

$$>\text{Al-OH}_2]^{+1/2} = >\text{Al-OH}]^{-1/2} + H^+$$

The fourth form of acidity is similar to the third.

In most instances soil acidity (both active and reserve) decreases with depth except for the Bialla Trial 205 profile which was relatively constant with depth and Popondetta soils where acidity increased with depth (Table 4.4 and Appendix 9 for profile depths). The high acidity at the surface in Hoskins, Kapiura and Bialla (201) soils is probably due to the accumulation of organic matter and the presence more variable-charged minerals compared to lower depths. Relatively constant pH for Bialla soils (Table 4.4 and Appendix 9 for 205 profile) is most likely due to their alluvial origin. The increase in acidity with depth in the Popondetta soils cannot be explained.

Table 4.4 Results Soil pH and Phosphate Retention at 0 - 30 cm Depths

Soil	Sample	Depth (cm)	P retention %	pH (1:2.5 H_2O)	pH 1M KCl	pH change	pH 1M NaF
Hoskins	107 NP	0 - 10	62	6.4	5.2	-1.2	10.3
		10 - 20	42	6.5	5.4	-1.1	10.3
		20 - 30	34	6.6	5.4	-1.2	10.1
	107 HP	0 - 10	68	6.1	5.1	-1	10.4
		10 - 20	49	6.4	5.4	-1	10.3
		20 - 30	33	6.6	5.4	-1.2	10.1
Kapiura	402 NP	0 - 10	62	5.9	4.9	-1	10.1
		10 - 20	53	6.3	5.3	-1	10.1
		20 - 30	44	6.5	5.3	-1.2	10.1
	402 HP	0 - 10	61	5.9	5.1	-0.8	10.2
		10 - 20	62	6.4	5.4	-1	10.5
		20 - 30	55	6.5	5.5	-1	10.4
Bialla	205 NP	0 - 10	87	6.1	5.3	-0.8	10.3
		10 - 20	93	6.3	5.4	-0.9	10.8
		20 - 30	96	6.2	5.4	-0.8	10.8
	205 HP	0 - 10	93	6	5.2	-0.8	10.6
		10 - 20	95	6.2	5.3	-0.9	10.8
		20 - 30	97	6.3	5.4	-0.9	10.9
	201	0 - 10	94	6.1	5.2	-0.9	11
		10 - 20	95	6.2	5.4	-0.8	11
		20 - 30	94	6.3	5.6	-0.7	11
Popondetta	323	0 - 10	31	6.3	5.6	-0.7	8.8
		10 - 20	31	5.3	4.3	-1	9
		20 - 30	33	5.5	4.6	-0.9	9.2
NZ Soils	Egmont	0 - 10	69	6.7	5.8	-0.9	10.3
	Taupo	0 - 10	55	4.3	4.2	-0.1	10.6
	Ramiha	0 - 10	65	4.9	4	-0.9	10

4.2.2 pH in 1M NaF and Phosphate Retention

4.2.2.1 pH in 1M NaF

Values for pH in 1M NaF in the Island region soils were generally higher than for Popondetta on the Mainland (Table 4.4). For Hoskins and Kapiura soils, $pH_{(NaF)}$ values range from 10.1 to 10.5 and are lower at lower depths (see Appendix 9). At these two sites it is mostly the topsoils that give high pH

For Bialla soils the values range from 10.3 to 11 and are also relatively constant at all depths. For Popondetta the overall values are much lower and range from 8.8 to 9.2; they are also relatively constant with depth (Appendix 9).

Large amounts of OH^- are released when NaF is added to Andisols which forms the basis of Fieldes and Perrott's (1966) rapid test for allophane. A $pH_{(NaF)}$ of >9.4 indicates the presence of amorphous minerals (Soil Survey Staff, 1975).

The generally high $pH_{(NaF)}$ (mostly >9.4) in the Island region soils reflects the abundance of high amounts of amorphous minerals in the soils as compared with Popondetta ($pH_{(NaF)}$, <9.4) soils which have low amounts of amorphous allophane. The pH values correlate well with results from the mineral studies where soils with high Al_o and Fe_o (Table 4.3) have $pH_{(NaF)}$ values greater than 9.4.

For Kapiura, Hoskins and Popondetta soils the lower $pH_{(NaF)}$ values at much lower depths in the Kapiura and Hoskins profiles (Appendix 9) and all depths for the Popondetta soil (Table 4.4) correlates well with the lower Alo and Feo values shown in Table 4.3. Obviously these soils contain less allophane and more unweathered materials than is the case for the Bialla soils.

Shoji and Ono (1978) and Mizota and Wada (1980) suggested $pH_{(NaF)}$ measured in volcanic soils that do not contain allophane also can show values greater than 9.4 due to Al-organic matter complexes. It was therefore suggested that the allophane test using pH in 1M NaF may not be specific for noncrystaline minerals such as allophane and imogolite but would at least indicate the pre-dominance of Al-OH groups in soils (Wada, 1980).

The ΔpH and pH in NaF are similar for PNG soils and the New Zealand Egmont and Ramiha soils being approximately 0.8 - 1 for ΔpH and greater than pH 10 for most of the pH (NaF) readings.

4.2.2.2 Phosphate Retention

4.2.2.2.1 Hoskins and Kapiura (107 and 402)

In the top 10 cm, PR of soils at Hoskins and Kapiura ranges from 61 to 73% (Table 4.4 and Appendix 9). PR in the Hoskins soils drops off with depth and this parallels decrease in allophane content shown previously in Tables 4.2 and 4.3.

At Kapiura PR values are relatively constant at 0 - 10, 10 - 20 and 20 - 30 cm depths (Table 4.4 and Appendix 9). This corresponds well with relatively constant levels of ferrihydrite and allophane throughout the 0 - 45 cm depth shown in Table 4.3.

The generally high PR values in the surface layers compared to lower values at lower depths (Appendix 9) is due mainly to the fact that more weathered materials occur in surface horizons as compared to relatively unweathered materials at lower depths.

4.2.2.2.2 Bialla Trials 205 and 201

Bialla soils have PR values that are mostly greater than 90% and are relatively constant for all depths (Table 4.4 for 0 - 30 cm at depth and Appendix 9 for Trial 205 profile).

The slightly lower PR values at 0 - 10 cm depth at Trial 205 (Table 4.4) are probably due to organic matter forming complexes with Al and Fe ions. Al and Fe humus complexes are commonly present in high amounts in surface soils developed from volcanic ash materials (Dahlgren *et al.,* 1993). Organic anions produced from decomposing organic matter also compete for anion adsorption sites and this reduces the P sorption capacity of soils (Uehara and Gillman, 1981). Even if there are complexes formed, the PR values in Bialla (Trial 205) are still very high. The high PR values at all depths indicates weathered volcanic ash materials which may have formed elsewhere and then been transported and deposited by water at this site.

The relatively constant PR values at all depths in Trial 201 is probably due to deep uniform weathering which has produced high amounts of secondary noncrystalline minerals at all depths. This site is on a stable landform as compared to Trial 205 which is on an alluvial plain.

4.2.2.2.4 Popondetta Trial 323

In trial 323 at Popondetta, the PR values are low and relatively constant at 31 to 33 % for all depths (Table 4.4). The low PR values correspond well with low $pH_{(NaF)}$ (Table 4.4). Low PR values in Popondetta soils also correspond well with low allophane and ferrihydrite levels (Table 4.3) and low allophane in clay minerals (Table 4.2).

The likely reason for low PR at Popondetta is that the volcanic ash materials are relatively very young and time has not been sufficient for weathering to form noncrystalline secondary minerals that are responsible for high PR capacities of soils.

Bleeker (1987) reported both low and very high PR values for soils in this area. Probably the high PR values are associated with soils from ashes deposited earlier than the 1951 eruption or are on sites with good drainage which has allowed for formation of amorphous secondary minerals.

4.2.3 Relationships Between Phosphate Retention and Oxalate - Extractable Al and Fe

As expected, PR values were strongly and positively correlated with Al_o and Fe_o across all soils and depths (Table 4.5).

Table 4.5 Correlation of Phosphate Retention with Al_o and Fe_o, for all Soils and Depths

	Oxalate Al	Oxalate Fe
Phosphate Retention	0.84 *	0.89*

* 5% significance level

When depths were considered separately the correlations were even stronger (Table 4.6).

Table 4.6 Correlation of Al_o and Fe_o with Phosphate Retention for all soils at Individual Depths

Depths (cm)	Oxalate Al	Oxalate Fe
0 - 10	0.97*	0.90*
10 - 20	0.98*	0.97*
20 - 30	0.99*	0.94*

* 5 % significance level

Regression equations between PR and the mineral (allophane and ferrihydrite) contents of soils determined by the acid-oxalate extract procedure shows ferrihydrite having a stronger relationship ($r^2 = 0.80$) than allophane ($r^2 = 0.60$) (Table 4.7)

Table 4.7 Regression Equations for Relationship between Phosphate Retention and Allophane and Ferrihydrite Content over all Soils and Depths

Relationship	r^2
P retention = 28.11 + 3.4 Allophane	0.60*
P retention = 15.55 + 26.76 Ferrihydrite	0.80*

* 5% Significant

The high Al_o and Fe_o in the Bialla soils (Trials 201 and 205) and correspondingly high PR contrast markedly with those found in Popondetta (Trial 323) where very low Al_o, Fe_o and PR are found. The Kapiura (Trial 402) and Hoskins (Trial 107) have Al_o and Fe_o levels that are intermediate between those from Bialla and Popondetta and likewise intermediate PR values of 60 - 70% in the top 30 cm of soil.

In no case was it possible to differentiate between Al_o and Fe_o as both occur together, and are formed via similar soil processes. In terms of absolute abundance, allophane is usually present in greater amounts (often by a factor of 2 -5) but at Popondetta the ferrihydrite:allophane ratio reverses to 2:1 (Table 4.3). Popondetta soils have low PR and logic would suggest therefore that Al is more important than Fe in this regard.

These oil palm growing soils could be classified into 3 general categories on the basis of PR and Al_o and Fe_o contents; viz,

a) Very high A_{lo}, Fe_o and very high PR - e.g. Bialla Soils.
b) High Al_o, Fe_o and high PR - e.g. Hoskins and Kapiura Soils.
c) Low Al_o, Fe_o and low PR - e.g. Popondetta Soils.

4.3 PHOSPHORUS FRACTIONATION

4.3.1 Introduction - P Fractions

Soil P was fractionated in two ways; (a) by sequential extraction according to the method of Hedley *et al.,* (1994) as shown in Figure 4.1, and (b) bicarbonate-extractable P was fractionated using the method of Bowman and Cole (1978b) to distinguish between soluble inorganic and soluble organic P in the Olsen soil test (Olsen, 1954).

The P fractions measured were then assigned to three major groups viz. readily-available P, not-so-readily available P (referred as "intermediate-P") and unavailable-P as shown in Figure 4.1.

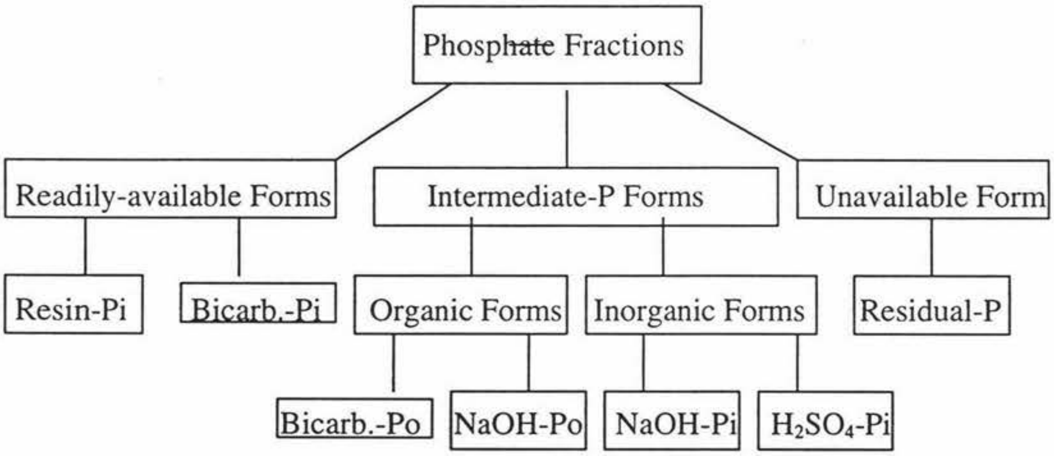


Figure 4.1 Phosphate Fractionation Scheme

Each of the P groups and fractions are explained below.

4.3.1.1 Readily Available P Forms

This fraction is normally regarded as most available for plant (Bowman and Cole, 1978a) and microbial use (Cross and Schlesinger, 1995). Included in this category are resin-Pi and bicarbonate Pi. Resin-Pi is Pi that is assumed to be freely plant available (Hedley *et al.*, 1994) along with bicarbonate Pi.

4.3.1.2 Less Readily-Available P Forms

Forms of P included in this category are not immediately available for crop uptake but may become available over a period of time. This P would not probably contribute very much to the nutrition of an annual crop but could be important for perennial tree crops like oil palm. P extracted in this fraction would include both organic and inorganic forms.

4.3.1.2.1 Organic P Forms

Of the organic P fractions, bicarbonate-Po represents a rapidly mineralisable pool of Po (Bowman and Cole, 1978a). NaOH-extractable Po on the other hand is usually considered to be that fraction of organic P that is held strongly by chemisorption to Al and Fe components of soil surfaces (Hedley *et al.*, 1994).

4.3.1.2.2 Inorganic P Forms

NaOH-Pi is taken to be a measure of Pi adsorbed on predominantly positively charged oxide surfaces (Hedley *et al.*, 1994). The strength of binding is sufficiently strong to overcome the repulsive forces of the like-charged surfaces and adsorbing anions.

H_2SO_4-Pi is assumed to be that P associated with negatively charged oxides surfaces via strong bonding through exchangeable cations and held mostly within oxide crystals (Hedley *et al.*, 1994). The P here is mostly in the primary apatite minerals and may include residual P fertilisers.

4.3.1.3 Unavailable P Fraction

Unavailable-P (residual-P) is P that is not normally likely to be available for plant uptake in the intermediate term and probably not even in the long term as well (Cross and Schlesinger, 1995). This P fraction probably includes remaining occluded P and recalcitrant organic forms of P (Hedley *et al.,* 1994).

In the following sections the major P forms and distribution of P are discussed for the individual soils used in this study.

4.3.2 Hoskins Soils

Total P in the 0 - 10 cm depth is very high (>1200 mg P /kg soil) for both nonfertilised and fertilised soils and decreases to 400 - 500 mg P/kg at lower depths (Table 4.8). At 0 - 10 cm depth, Total-P increases from 1309.5 to 1611.9 mg P /kg soil (23% increase) due to fertilising. Total P at 10 - 20 and 20 - 30 cm depths are lower and each accounts for less than 40 % of their respective total P at 0 - 10 cm depth both in nonfertilised and fertilised soils. High Total P at 0 - 10 cm depth is most likely related to accumulation of organic matter in the surface A horizon.

The major, potential long-term plant-available P fraction would appear to be NaOH-Po; accounting for approximately 36 to 48% of total P content for all depths and for both fertilised and nonfertilised soils alike (Figure 4.2 (a)). The next most abundant forms for all soils and depths are NaOH-Pi and H_2SO_4-P. Resin-Pi is the smallest fraction, comprising less than 3% of the total P extracted for soils and at all depths.

Of the bicarbonate extracts, Bicarb.-Pi is the dominant P fraction making up more than 65% of total bicarbonate-P (Figure 4.2 (b)).

The residual P fraction is also a major P fraction (21 - 41% of total-P) at the 0 - 10 cm depth but at the lower two depths this fraction accounts for less than 13% of total P in both nonfertilised and fertilised soils.

Most of the fractions, except for H_2SO_4-Pi, decrease with depth.

Fertiliser applications increased all fractions of P except residual P, especially at 0 - 10 cm depth. There was also a slight increase in Resin-Pi, NaOH-Pi, NaOH-Po and residual-P at 10 - 20 cm depth due to fertiliser application. In the case of Bicarb.-Po and Pi, the effect of fertiliser addition was detected at all depths, with the main increase being found, as expected in the top 10 cm of soil.

Table 4.8 Phosphorus Fractions in mg P /kg (% of Total-Extractable P is shown in Parenthesis)

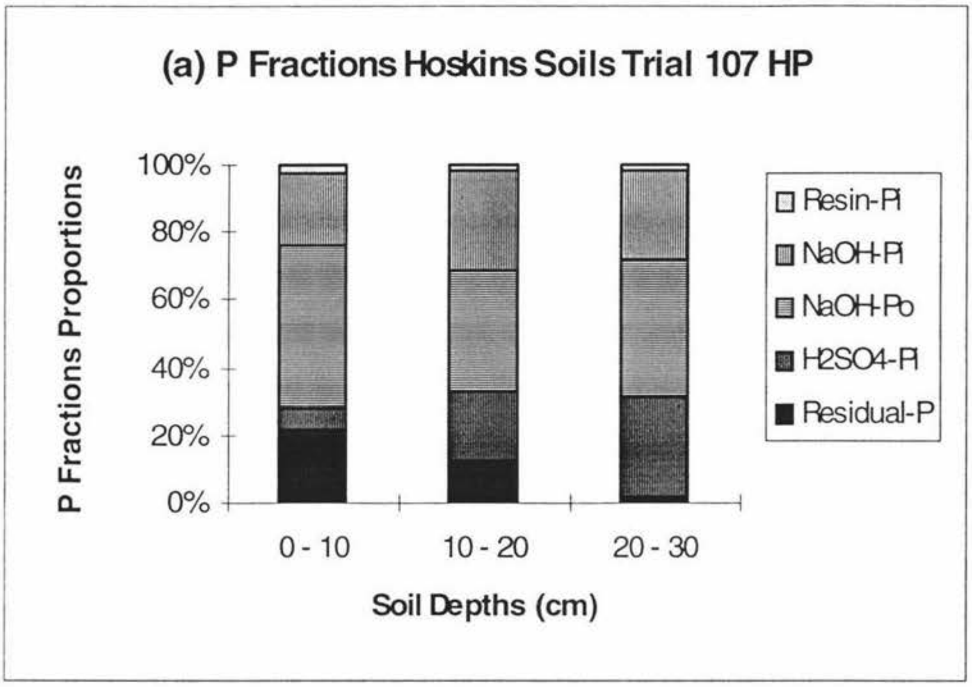
Site	Sample	Depth (cm)	P Fractions from Sequential Extraction (mg P/kg)							Bicarbonate Extractable P (mg P/kg)		
			Resin-Pi	NaOH-Pi	NaOH-Po	H_2SO_4 -Pi	Residual-P	Total P		Bicarb.-Pi	Bicarb.-Po	Total Bicarb. P
Hoskins	107 NP	0 - 10	14.8	186.2	494.2	71.6	542.7	1309.5		6.6	3.7	10.3
			(1)	(4)	(38)	(5)	(41)			(65)	(35)	
		10 - 20	7.2	129.5	156.3	116	29.9	434.9		2.9	0	2.9
			(1)	(30)	(36)	(27)	(7)			(100)		
		20 - 30	6.7	110.1	244.5	147.7	16.4	525.1		2.7	0	2.7
			(1)	(21)	(47)	(28)	(3)			(100)		
	107 HP	0 - 10	34.6	350.7	778.6	103.8	344.3	1611.9		16.2	4.4	20.6
			(2)	(22)	(48)	(6)	(21)			(79)	(21)	
		10 - 20	8.4	146.5	179.2	101.6	62.6	498.4		4.2	0.3	4.5
			(2)	(29)	(36)	(20)	(13)			(93)	(7)	
		20 - 30	7.2	122.9	189.1	140	8.6	467.7		3.3	0.7	4
			(1)	(26)	(40)	(30)	(2)			(83)	(17)	
Kapiura	402 NP	0 - 10	18.1	89.6	278.6	94.4	517.7	998.5		4.8	8.7	13.5
			(2)	(9)	(28)	(9)	(52)			(35)	(65)	
		10 - 20	10.8	60.1	371	101.1	276.3	819.3		2.6	3.5	6.1
			(1)	(7)	(45)	(12)	(34)			(42)	(58)	
		20 - 30	2.7	39.9	322.1	86.2	80.2	531.1		2	2.5	4.5
			(0.5)	(6)	(61)	(16)	(15)			(45)	(55)	

Table 4.8 continued

Site	Sample	Depth (cm)	P Fractions from Sequential Extraction (mg P/kg)							Bicarbonate Extractable P (mg P/kg)		
			Resin-Pi	NaOH-Pi	NaOH-Po	H_2SO_4 -Pi	Residual-P	Total P		Bicarb.-Pi	Bicarb.-Po	Total Bicarb. P
Kapiura	402 HP	0 - 10	52.7	350.6	840	153.9	488.4	1885.5		23.4	7.1	30.5
			(3)	(19)	(45)	(8)	(26)			(77)	(23)	
		10 - 20	6.8	69	383	73.4	224.4	756.6		2.4	9.1	11.5
			(1)	(9)	(51)	(10)	(30)			(21)	(79)	
		20 - 30	6.3	63.3	620.3	41.7	112.9	844.4		1.8	4.9	6.7
			(1)	(7)	(73)	(5)	(13)			(27)	(73)	
Bialla	205 NP	0 - 10	16.3	40.6	625.3	67.9	456.7	1206.9		3.9	8.6	12.5
			(1)	(3)	(52)	(6)	(38)			(31)	(69)	
		10 - 20	5.7	105.3	595.7	67	352.4	1126.1		1.9	7.9	9.8
			(0.5)	(9)	(53)	(6)	(31)			(20)	(80)	
		20 - 30	4.4	93.8	643.9	71.6	347.2	1160.9		1.4	5.4	6.8
			(0.4)	(8)	(55)	(6)	(30)			(21)	(79)	
	205 HP	0 - 10	14.8	94	776.1	75.5	280.4	1240.8		3.6	7.8	11.4
			(1)	(8)	(63)	(6)	(23)			(31)	(69)	
		10 - 20	7.4	95.8	766.9	74.8	313.7	1258.4		1.8	6.5	8.3
			(0.6)	(7)	(61)	(6)	(25)			(22)	(78)	
		20 - 30	5	80.3	712	75.4	259.2	1131.9		1.2	5.6	6.8
			(0.4)	(7)	(63)	(7)	(23)			(17)	(83)	

Table 4.8 continued

Site	Sample	Depth (cm)	P Fractions from Sequential Extraction (mg P/kg)							Bicarbonate Extractable P (mg P/kg)		
			Resin-Pi	NaOH-Pi	NaOH-Po	H_2SO_4 -Pi	Residual-P	Total P		Bicarb.-Pi	Bicarb.-Po	Total Bicarb. P
Bialla	201	0 - 10	7	151.1	1398.2	60.8	445.5	2062.6		1.8	8.5	10.3
			(0.3)	(7)	(68)	(3)	(22)			(18)	(72)	
		10 - 20	4.6	120.1	1167.9	52.4	335.5	1680.3		1.3	5.7	7
			(0.3)	(7)	(70)	(3)	(20)			(18)	(72)	
		20 - 30	3	81.8	1152.9	33.1	92.3	1363		0.9	4.7	5.6
			(0.2)	(6)	(85)	(2)	(7)			(17)	(83)	
Popondetta	323	0 - 10	10.4	120	642.9	61.6	140.8	975.7		4.6	9.7	14.3
			(1)	(12)	(66)	(6)	(14)			(32)	(68)	
		10 - 20	12.3	107.4	483.9	62.1	143.8	809.5		3.9	8.7	12.6
			(2)	(13)	(60)	(7)	(18)			(31)	(69)	
		20 - 30	8.4	107.3	445.3	67.4	157.5	786		3.9	4.5	8.4
			(1)	(14)	(57)	(8)	(20)			(46)	(54)	
NZ Soils	Egmont	0 - 10	15.9	578.1	972.4	241	404.8	2212.2		6.5	5.3	11.8
			(7)	(26)	(44)	(11)	(18)			(55)	(45)	
	Taupo	0 - 10	12	349.2	742.3	58.8	30.2	1206.2		14.7	7.6	22.3
			(1)	(29)	(62)	(5)	(3)			(66)	(34)	
	Ramiha	0 - 10	13.6	268.3	754.8	67	115.2	1218.4		16.5	14.6	30.1
			(1)	(22)	(62)	(6)	(9)			(51)	(49)	



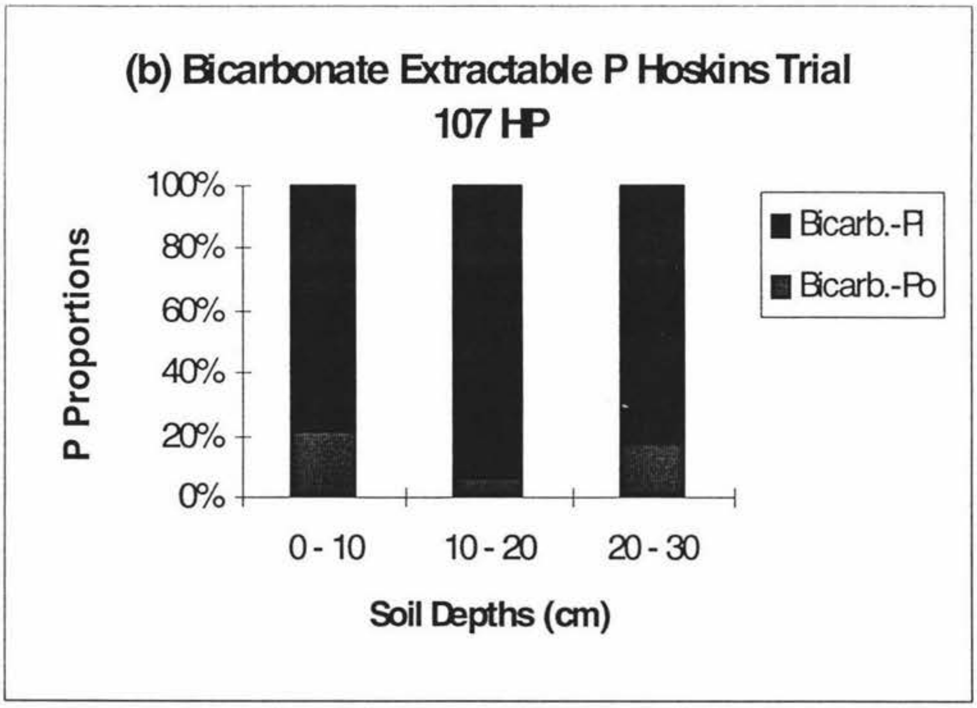


Figure 4.2 Relative proportions of P fractions in Hoskins soils

4.3.3 Kapiura Soils

Total-P levels in Kapiura soils are generally high (>1000 mg P/kg soil) at 0 - 10 cm depth and decrease gradually with depth (Table 4.8). Total-P increased from 998.5 to 1885.5 mg P /kg soil (about 88 % increase) at 0 -10 cm depth as a result of fertiliser application. Total-P at the lower two depths comprises between 50 and 80% of total P at 0 - 10 cm depth in nonfertilised soil and 40 and 45% in the fertilised soil. High Total-P values in the top 10 cm in both nonfertilised and fertilised soils is related to accumulation of organic matter at the soil surface.

In both the fertilised and nonfertilised Kapiura soils, organic-P fractions would appear to be the major long term plant available form present (Figure 4.3). NaOH-Po accounts for, on average, 45% (range 28 - 61%) of total P in nonfertilised soils and 56% (range 45 - 73%) in fertilised soils at all soil depths. Apart from residual-P, the next two major potential plant-available forms would appear to be NaOH-Pi and H_2SO_4-Pi both making up an average of 10% each of total P at the different depths. Resin-Pi is the smallest P fraction amounting to less than 3 % of total P for the different depths in both fertilised and nonfertilised soils.

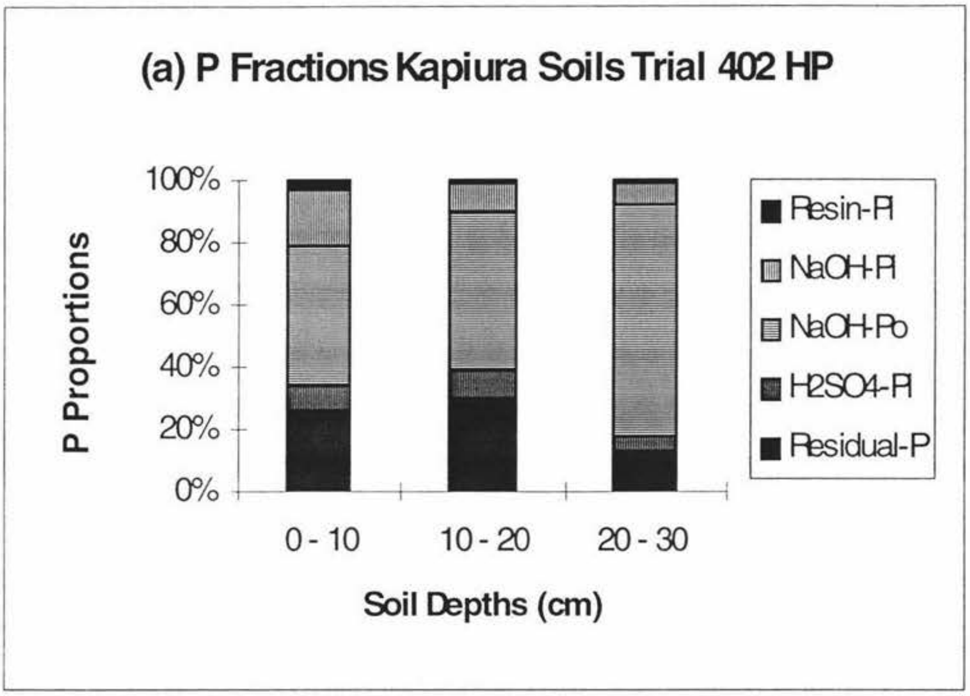
Bicarb.-Po is the dominant P form in the bicarbonate extracts; accounting for an average of 60% of total bicarbonate-extractable P for all depths in both fertilised and nonfertilised soils, except at 0 - 10 cm depth in the fertilised soils (Figure 4.3 (a)). At this depth in the case of the fertilised soil most of the P was recovered in the Bicarb.-Pi form and this suggests that recently-added P fertiliser may be still present in readily-available form for plant uptake.

Residual-P is also a prominent form but only at the 0 - 10 cm depth.

All P fractions decrease with depth except for NaOH-Po and H_2SO_4-Pi which remain relatively constant with depth in the nonfertilised soils.

All P fractions also increase with P fertiliser additions except for residual P. The increase is mostly at 0 - 10 cm and 20 - 30 cm depths. Bicarb.-Pi increases only at 0 - 10 cm depth whereas Bicarb.-Po increases at all depths.

Comparing Hoskins and Kapiura soils which are both derived from the same volcanic ash parent materials, organic P contents in Kapiura soils are generally higher than in Hoskins. Oil palm production on Hoskins soils has occurred for a longer period than at Kapiura and it seems P in organic forms may have been depleted to meet the palm requirements over time at the Hoskins site.


(a) P Fractions Kapiura Soils Trial 402 HP

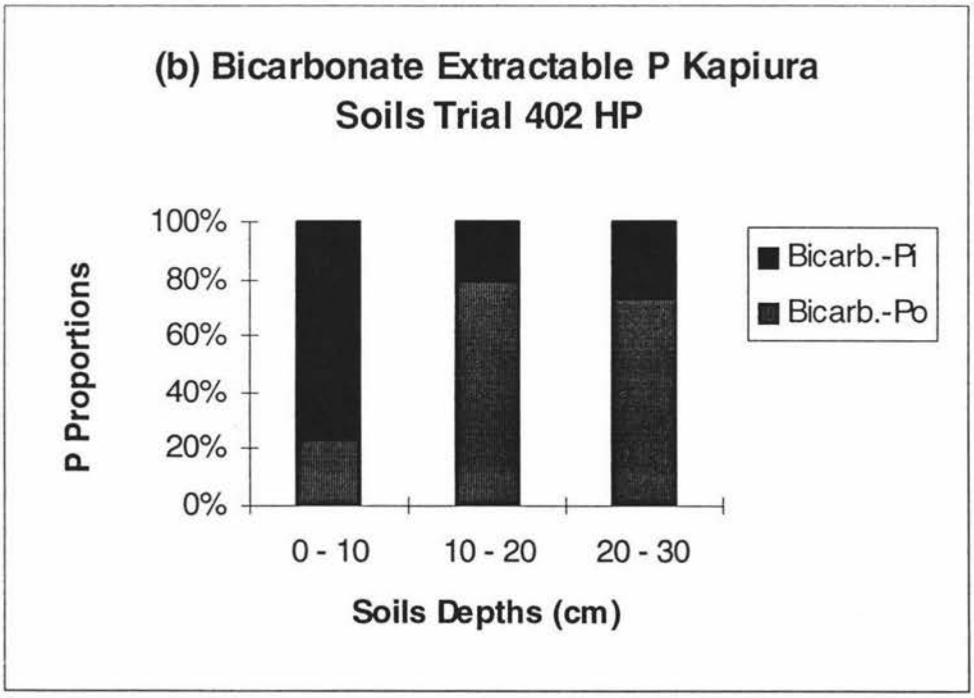

(b) Bicarbonate Extractable P Kapiura Soils Trial 402 HP

Figure 4.3 Relative proportions of P fractions in Kapiura Soils

4.3.4 Bialla Soils (Trials 201 and 205)

Bialla soils have very different amounts and patterns of distribution of the different P fractions and total-P.

Total-P in Bialla soils is generally high to very high (>1100 mg P / kg soil) at all soil depths (Table 4.8). Total-P at Trial 205 is relatively constant with depth but at Trial 201 it decreases with depth.

Again the main plant available P fractions in Bialla soils would appear to be the organic P forms.

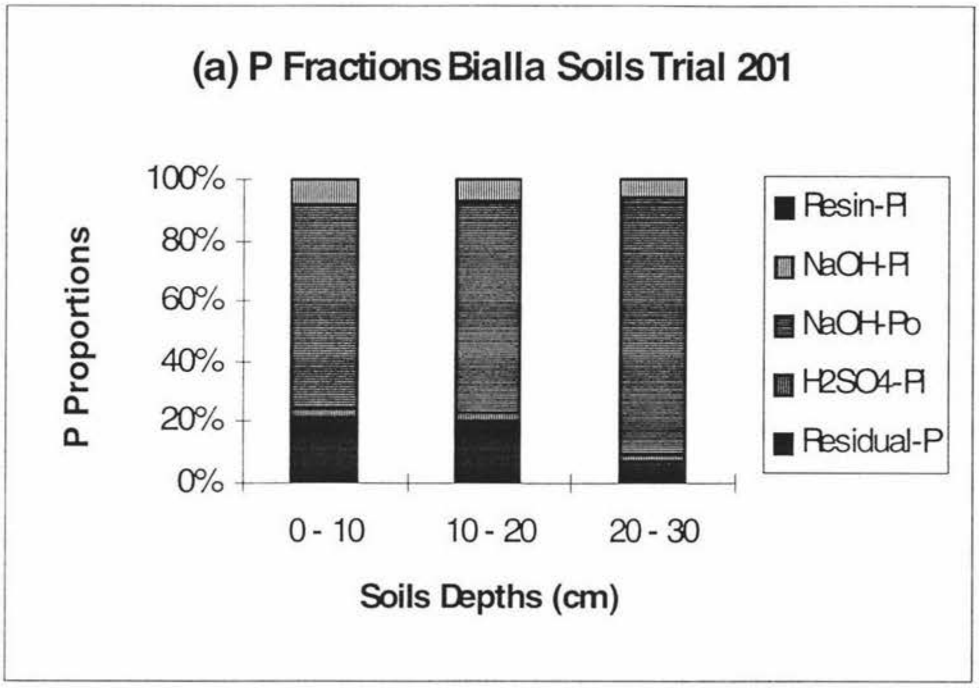
Fractionation reveals that NaOH-Po is the major fraction accounting for 52 to 63% of total P in Trial 205 and 68 to 85% in Trial 201 at all depths (Figure 4.4). NaOH-Pi and H_2SO_4-Pi are the next two major plant available forms accounting for between 3 and 9% of total P for all depths. Resin Pi in both soils is the smallest fraction being less than 1% of total P in Trial 205 and 0.3% in Trial 201.

For the bicarbonate extracts Bicarb.-Po is the major P fraction accounting for 69 to 83% of total bicarbonate extractable P in both trials at all depths (Figure 4.4 (b)).

There is also a considerable amount of residual-P in both soils although this fraction is not considered readily-available for crop use.

Most of the P fractions in Trial 205 are relatively constant with depth (whether expressed as absolute amounts or as percentages of total-P) but Resin-Pi, Bicarb.-Pi and Bicarb.-Po all tend to decrease with depth.

In Trial 201 all P fractions decrease with depth except for NaOH-Po which is relatively constant down the profile.



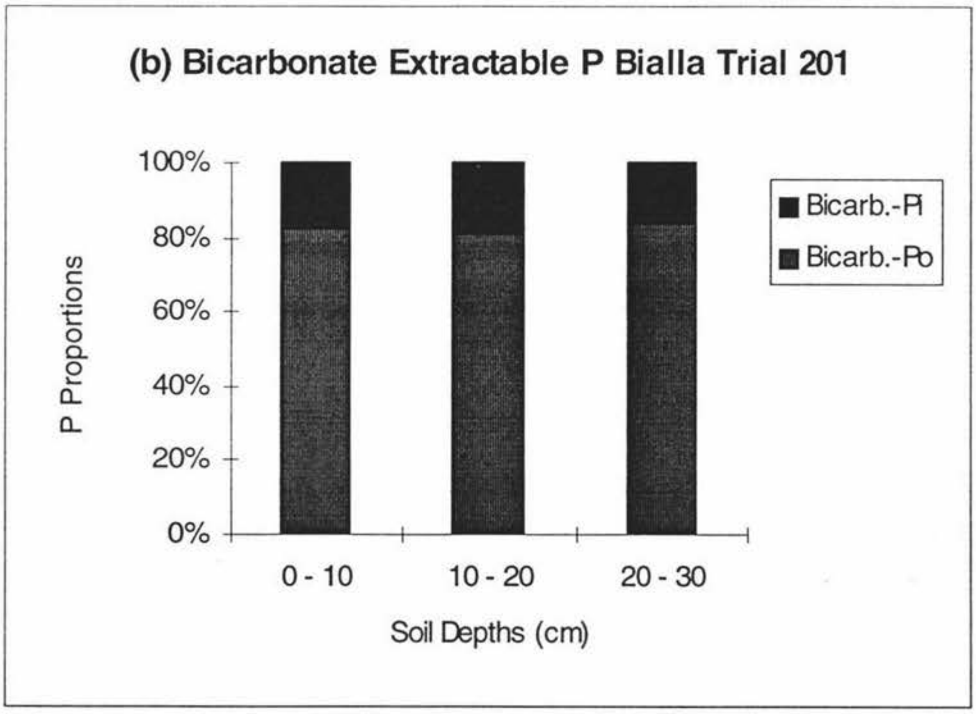


Figure 4.4 Relative proportions of P fractions in Bialla Trial 201 soils

4.3.5 Popondetta Soils (Trial 323)

Total-P in Popondetta soils is slightly higher at 0 - 10 cm (975 mg P/kg) than 10 - 20 cm (809 mg P/kg) and stays relatively constant down to the 20 - 30 cm depth (Table 4.8). Enrichment of total-P at the 0 - 10 cm soil is probably due to organic matter accumulation at the soil surface.

Again the major plant available P forms in Popondetta soil would appear to be organic. NaOH-Po is the dominant fraction accounting for an average 62% (range 57 - 66%) of the total P over all depths. This is followed by Noah-Pi with an average of 13% and H_2SO_4-Pi with an average of 7% across all depths. Resin-Pi is the smallest fraction being less than 3% of total P at all depths.

In the case of bicarbonate extracts, Bicarb.-Po is the major fraction at an average of 63% (range 54 - 69%) of total bicarbonate extractable P over all depths.

Residual-P makes up only 7% of total P averaged over all depths.

All the P fractions remain relatively constant down the profiles except for NaOH-Po and Bicarb.-Po which tend to decrease with depth.

4.3.6 New Zealand Soils

Total P in Egmont soils is higher (nearly double) than is the case for Taupo and Ramiha soils (Table 4.8).

As with PNG soils the major plant available P form is probably NaOH-Po in all soils. This form accounts for 44 to 60% of total P. NaOH-Pi is the second most abundant form being within the range 22 to 29% of total P (only half that of NaOH-Po). H_2SO_4-Pi is also a common P form and is highest for Egmont soils at 11% of total P as compared with 5 and 6% for Taupo and Ramiha soils, respectively. For all soils Resin-Pi accounts for less than 1% of total P.

With the bicarbonate extracts, Bicarb.-Po and Pi are of approximately equal amounts in Egmont and Ramiha soils but Pi is greater than Po in Taupo soil (by nearly 2:1). All New Zealand soils are relatively low in bicarbonate extractable P, especially Egmont.

4.3.7 Comparison Amongst PNG Soils

The gradient of change in Total-P and Total Bicarb.-P at Bialla and Popondetta soils with depth is small by comparison with the trends in Hoskins and Kapiura where a major decrease with depth is seen and most of the total P (Total-P and Total Bicarb. P) occurs are found in the surface 10 cm (Table 4.8)

Bialla and Popondetta soils have higher organic P contents (> 60% of total P) on average for all soil depths as compared with Hoskins and Kapiura soils (Table 4.9). In all PNG soils organic P fractions are the major form.

Table 4.9 Average Organic P Percentage for all Soil Depths for PNG Soils

	Sites				
Organic P Form	Hoskins	Kapiura	Bialla		Popondetta
			(201)	(205)	
NaOH-Po	40	50	74	58	62
Bicarb.-Po	13	59	76	76	63

All P fractions in Popondetta are relatively constant in absolute amounts, with depth. In Bialla, all P fractions are also relatively constant with depth except for Resin-Pi and Bicarb.-Pi which tend to decrease while in Hoskins and Kapiura soils, Resin-Pi, NaOH-Pi, NaOH-Po and residual-P all significantly decrease with depth (Table 4.8).

4.3.8 Comparison Between PNG and New Zealand Soils

For both NZ and PNG soils organic P is an important fraction of total-P. Except for Bialla soils, organic P in NZ soils are generally higher than the PNG soils. Obviously the rate of accumulation of organic P is less under tropical conditions in PNG than is the case for temperate conditions as in NZ.

NaOH-Pi also tends to be a dominant P fraction in all soils. In the case of NZ soils this form is generally much more significant than in PNG soils. For example whereas NaOH-Pi in the NZ soils ranges from 268 for Ramiha to 578 mg/kg for Egmont soil, it is less than 100 mg/kg for most of the PNG soils with the maximum of 180 mg P/kg found in Hoskins unfertilised soils. Due to fertilising in Hoskins and Kapiura NaOH-Pi rises to 350 mg/kg in both soils at the 0 - 10 cm depth.

No clear pattern exists for the other P fractions which varied for the different soils analysed.

4.4 PHOSPHORUS ACCUMULATION FROM FERTILISER APPLICATIONS

Soils from Hoskins and Kapiura were used to evaluate P build up from previous fertiliser applications. Fertilised and nonfertilised trial plots were separately sampled. Fertilised plots had received fertilisers for up to 7+ years for Hoskins (Trial 107) and 6 for Kapiura (Trial 402). Bialla (Trial 205) could not be used for this study as the soil had only received its first application of fertiliser at the time of sampling. Soils were sampled to 30 cm in all cases.

Oil palms at Hoskins (Trial 107) were replanted in 1983, at a density of 135 palms /ha. TSP fertiliser application commenced in 1985 at the rate of 1kg/palm/year; a rate which was maintained for the subsequent 4 years. The rate was then increased to 2kg/palm/year in 1989 and continued at this rate up until the end of 1996 (7+ years) when the soil samples were taken.

At Kapiura, palms were planted in 1987 at a density of 120 palms/ha from virgin forest. TSP fertiliser treatments commenced in 1990 at the rate of 4kg/palm/year and this has been the rate up until sampling at the beginning of 1997 (i.e 6 years of continuous fertiliser addition).

For the calculations it is assumed that fertiliser is applied to a 1m band around the palms at a distance of 2.5 m away from the centre of the palm base. Therefore radius to the end of the banded area is 2.5 m (r_1) and to the edge of weeded circle is 1.5 m (r_2) (Figure 4.5). Calculations for accumulated P were done as follows:

Fertilised Area/ Palm = Total Area - (Area of Weeded circle + Palm Base)

$$= \pi r_1^2 - \pi r_2^2$$

$$= \pi(2.5)^2 - \pi(1.5)^2$$

$$= 12.57 \text{ m}^2$$

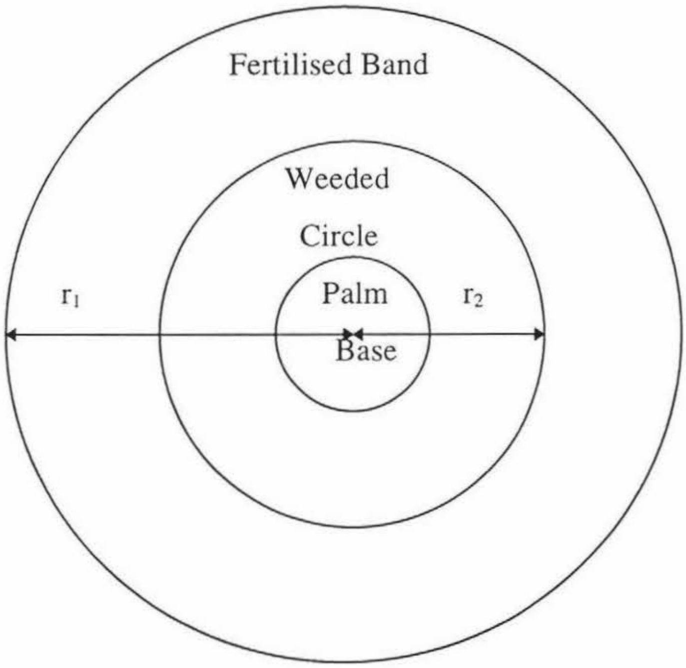


Figure 4.5 Outline of Fertilised Area per Oil Palm Tree

For Hoskins with palms replanted at 135 palms /hectare, total fertiliser applied in the banded area per hectare is = planting density X fertilised area /palm

= 135 X 12.57

= 1697 m^2/ha

For Kapiura with palms planted at 120 palms /hectare, total fertiliser applied in the banded area per hectare is = planting density X fertilised area /palm

= 120 X 12.57

= 1508 m^2/ha

The calculations above show that only about 15 - 17% of the soil in each hectare receives fertiliser.

Soil volumes were calculated for the 2 soils to 0.1 m depths and this was multiplied by the soil bulk density of 700 kg/m^3 (PNGOPRA Annual Report, 1990) to get the fertilised soil per hectare. The fertilised soil per hectare was then multiplied by the difference in measured P between fertilised and nonfertilised soils and adjusted to a per hectare basis by multiplying by 5.89 (10000/1696.95) for Hoskins and 6.63 (10000/1508.4) for Kapiura. This was done to place the figures on an "effective" hectarage basis so as to be able to relate fertiliser applications to the more normal whole-soil basis, rather than to per square metre basis (in which only a fraction of each hectare receives the banded fertiliser).

Calculations were done for whole soils (Total P) for different depths, and for P fractions that showed positive accumulations of P.

The results show that in both soils most of the P accumulates in the 0 - 10 cm depth (Table 4.10). Actual figures being 83% of the total accumulated P for Hoskins and 74% for Kapiura.

Table 4.10 Total Soil P Contents of Fertilised and Nonfertilised Soils at Hoskins (107) and Kapiura (402)

Soil/Site	Depth (cm)	Total P Control (mg/kg)	Total P Fertilised (mg/kg)	Difference (mg/kg)	Accumulated P (kg/ha)
Hoskins	0 - 10	1309.5	1611.9	302.4	211.7 (83)
(107)	10 - 20	434.9	498.4	63.5	44.4 (17)
	20 - 30	525.1	467.7	-55	----
				Total	256.1 (100)
Kapiura	0 - 10	998.5	1885.6	887	620.9 (74)
(402)	10 - 20	819.3	756.6	-62.7	----
	20 - 30	531.1	844.4	313.3	219.3 (26)
				Total	840.2 (100)

( ) = % of total accumulated P

In both soils there is a measurable accumulation at lower depths. For Hoskins soil 17% of the total applied P was found at the 10 - 20 cm depth but none appears to have accumulated at 20 - 30 cm depth.

For Kapiura soil there was no measurable accumulation at 10 - 20 cm depth but a significant amount (26% of total accumulated P) was detected at 20 - 30 cm depth. The amounts involved for the Kapiura subsurface horizons are difficult to determine due to errors in measuring total P. It is not possible to reconcile the non-accumulation in the 10 - 20 cm horizon with that occurring above and below this layer.

The negative values are due to errors in sampling, soil variability in the field and errors associated with total P determination.

In a study of P accumulation in NZ pastures on andesitic volcanic soils in the North Island, Saunders (1959) reported similarly that most of the P accumulated in the top 5 cm layer of the soils with very little reaching lower depths.

In this study any P accumulation found at lower depths could be due to one or more of the following:

a) leaching of soluble organic P from upper layers

b) leaching of Pi followed by adsorption to organic matter or minerals at depth

c) in situ P release from dead roots and root exudates at lower depths

d) mixing of top soils by earthworms and other soil organisms.

Of these possibilities (c) and (d) seem unlikely because of the discontinuity evident in the data. Hence the first two are more likely to explain the findings. Leaching of inorganic P on these high PR soils is also unlikely. P movement down the profile as soluble organic-P cannot be discounted and this looks the most likely option to explain P movement below the top 15 cm in these trials. Larger apparent accumulation at 20 - 30 cm with none at 10 - 20 cm depth at Kapiura remains unexplained.

It is clear that at both trial sites at 0 - 10 cm depth more than half the P has accumulated in the NaOH-Po; 53% for Hoskins and 61% for Kapiura. The next most abundant form was NaOH-Pi followed by H_2SO_4-Pi and Resin-Pi (Tables 4.11 and 4.13).

At the lower 2 depths for both soils the same general results were found with NaOH-Po being the major fraction (Tables 4.12 and 4.14).

Table 4.11 P Accumulation of P Fractions in Hoskins soils at 0 - 10 cm Depth

P Fraction	Control (mg/kg)	Fertilised (mg/kg)	Difference (mg/kg)	Amount of Accumulated P (kg/ha)
Resin-Pi	14.8	34.6	19.8	13.9 (4)
NaOH-Pi	186.2	350.7	164.5	115.2 (37)
NaOH-Po	494.2	778.6	284.4	199.1 (53)
H_2SO_4 -Pi	71.6	103.8	32.2	22.5 (6)
Residual-P	542.7	344.3	-198.4	
			Total	250.7 (100)

( ) = % of total accumulated P

Table 4.12 P Accumulation of P Fractions in Hoskins soils at 10 - 20 cm Depth

P Fraction	Control (mg/kg)	Fertilised (mg/kg)	Difference (mg/kg)	Amount of Accumulated P (kg/ha)
Resin-Pi	7.2	8.4	1.2	0.84 (2)
NaOH-Pi	129.5	146.5	17	11.9 (23)
NaOH-Po	156.3	179.2	22.9	16 (31)
H_2SO_4-Pi	116	101.6	-10.1	
Residual-P	29.6	62.6	32.7	22.9 (44)
			Total	51.6 (100)

( ) = % of total accumulated P

Table 4.13 P Accumulation of P Fractions in Kapiura soils at 0 - 10 cm Depth

P Fraction	Control (mg/kg)	Fertilised (mg/kg)	Difference (mg/kg)	Amount of Accumulated P (kg/ha)
Resin-Pi	18.1	52.7	34.6	24.2 (4)
NaOH-Pi	89.6	350.6	261	182.7 (28)
NaOH-Po	278.6	840	561.4	393 (61)
H_2SO_4-Pi	94.4	153.9	59.5	41.6 (6)
Residual-P	517.7	488.4	-29.3	
			Total	641.5 (100)

( ) = % of total accumulated P

Table 4.14 P Accumulation of P Fractions in Kapiura soils at 20 - 30 cm Depth

P Fraction	Control (mg/kg)	Fertilised (mg/kg)	Difference (mg/kg)	Ammount of Accumulated P (kg/ha)
Resin-Pi	2.7	6.3	3.6	2.5 (1)
NaOH-Pi	39.9	63.3	23.4	16.4 (6)
NaOH-Po	322.1	620.3	298.2	208.7 (81)
H_2SO_4-Pi	86.2	41.7	- 44.5	
Residual-P	80.2	112.9	32.7	22.9 (11)
			Total	250.5 (100)

( ) = % of total accumulated P

There was some evidence of P accumulation as Residual-P at the lower 2 depths at both sites and this might be attributed to strongly adsorbed Pi and Po that was not extracted by NaOH.

Jackman (1955) previously reported that 80% of total accumulated P in yellow brown pumice soils, in NZ, was in the organic form. Perrott and others (1989) showed that Po was the major P form accumulating under pasture soils but that the accumulation exhibited a curvilinear relationship with total P whereas inorganic P fractions showed a linear relationship. The curvilinear relationship was taken to indicate that Po accumulation was reaching an equilibrium. By contrast, the Pi forms kept increasing and showed no tendency to reach a steady state situation. Jackman (1964) reported a decrease in the rate of Po accumulation after 30 years of top dressing with P fertiliser with Po forms approaching an equilibrium level.

High amounts of organic P found in surface soils are assumed to be due to the accumulation of organic matter resulting from increased plant growth in response to P fertilisers and their residues (Anderson, 1980).

High levels of Al_o and Fe_o in the top soil (Table 4.3) may be responsible for the accumulation of organic P in these PNG soils. Al_o and Fe_o probably form complexes with organic P compounds and also adsorb Pi. The H_2SO_4-Pi accumulating in the surface soils may be due to forms of Ca-phosphate such as dicalcium phosphates which are formed as TSP dissolution occurs in fertilised soils.

4.5 TOTAL CARBON AND NITROGEN ANALYSIS

Total C and N analyses were done to investigate the presence of buried soil horizons in the soils used in this study.

Results of these analyses, for all soils show a general trend of decreasing C and N with depth (Table 4.15) with some exceptions that are discussed below. High amounts at 0 - 10 cm depth in all soils obviously relate to accumulation of organic matter in these surface horizons.

For Hoskins soils however, whereas C and N generally decrease with depth, an elevated level at 70 - 175 cm in the profile strongly suggests the presence of a buried soil. This finding confirms the report by Bleeker and Parfitt (1974) of the existence of buried soils in the Cape Hoskins area. There is a steep decline in total C and N from the top 10 cm depth to 20 cm and 30 cm depths. This implies the existence of a very thin A horizon in Hoskins soils and probably the soils at this site are much younger than the other PNG soils used in this study. The C:N ratio is less than 10:1 and relatively constant at all depths in this soil.

For Kapiura, total C and N decrease with depth unlike the situation for Hoskins, there is no indication of any buried soil at lower depths. Total C and N are relatively high down to about 20 cm depth and then decrease, though not as steeply, as at Hoskins. The C:N ratio of Kapiura soil is different from the other PNG soils in that it decreases with depth even though there is very little organic matter below 20 cm. Kapiura soils are deeper than Hoskins soils with at least 20 to 30 cm of topsoil in contrast to the 10 - 15 cm for Hoskins.

At Bialla, total C and N also decrease with depth but the overall values are higher than for the other PNG soils, at all depths. Also the gradient of the fall in C and N is much less steep. High C and N levels in the Trial 205 profile are probably related to the alluvial nature of the soils at this site. There is a fluctuating water table at this site as indicated by the presence of mottles (Appendix 3), and this may slow the break-down of organic matter at lower depths leading to the relatively high C and N values. The presence of high allophane and ferrihydrite contents at all depths, as reported earlier (4.1.2), may also be responsible, by complexing organic matter in a form that is unavailable for mineralisation. The C:N ratio in Bialla soils is relatively constant at all depths, ranging from 9.71 to 10.96.

At Popondetta, total C and N also decrease with depth but the gradient of the decline is not as steep as for Hoskins soils. C:N ratios in Popondetta soils are relatively constant with depth and slightly higher than all other PNG soils. Popondetta soil has the highest C:N ratio of all the PNG soils but the lower horizons (10 - 20cm, 20 - 30 cm) have more C than Hoskins and less than the Bialla soils.

Total C and N in the 3 NZ soils are very high and are higher than all the PNG soils except for Bialla. The C:N ratios are also higher than in all PNG soils. The high C:N ratio values presumably reflect differences in the types of humic substances in PNG and NZ systems. A higher C:N ratio suggests there is less N for each unit of carbon. The narrower C:N ratios in PNG soils may indicate more rapid turnover of organic carbon in the warm, moist tropical conditions.

Table 4.15 Total Soil C, N and C:N Ratios for PNG and NZ Soils

Soil	Sample	Depth (cm)	Carbon (%)	Nitrogen (%)	C:N Ratio
Hoskins	107 NP	0 - 10	2.97	0.34	8.74
		10 - 20	0.69	0.09	7.67
		20 - 30	0.37	0.05	7.40
	107 HP	0 - 10	3.73	0.38	9.82
		10 - 20	0.99	0.11	9.00
		20 - 30	0.37	0.06	6.17
	Profile	0 - 15	4.63	0.49	9.45
		15 - 35	0.43	0.06	7.17
		35 - 70	0.73	0.09	8.11
		70 - 100	0.89	0.12	7.42
		100 - 175	0.95	0.13	7.31
		175 - 200	0.54	0.07	7.71
Kapiura	402 NP	0 - 10	5.54	0.58	9.55
		10 - 20	2.38	0.27	8.81
		20 - 30	0.89	0.11	8.09
	402 HP	0 - 10	5.01	0.51	9.82
		10 - 20	2.39	0.27	8.85
		20 - 30	1.33	0.16	8.31
	Profile	0 - 10	4.6	0.46	10.00
		10 - 23	2.31	0.25	9.24
		23 - 45	0.39	0.07	5.57
		45 - 70	0.18	0.04	4.50
		70 - 105	0.08	0.04	2.00
		105 - 133	0.05	0.03	1.67
		133 - 200	0.06	0.03	2.00
Bialla	Profile	0 - 15	7.47	0.72	10.38
	(205)	15 - 40	4.5	0.46	9.78
		40 - 70	3.11	0.3	10.37
		70 - 170	2.51	0.25	10.04
		170 - 200	2.04	0.21	9.71
	201	0 - 10	5.7	0.52	10.96
		10 - 20	4.32	0.44	9.82
		20 - 30	2.94	0.29	10.14
Popondetta	323	0 - 10	2.65	0.21	12.62
		10 - 20	1.86	0.16	11.63
		20 - 30	1.18	0.11	10.73

Table 4.15 continued

Soil	Sample	Depth (cm)	Carbon (%)	Nitrogen (%)	C:N Ratio
NZ Soils	Egmont	0 - 10	6.03	0.47	12.83
	Taupo	0 - 10	3.87	0.28	13.82
	Ramiha	0 - 10	6.75	0.48	14.06

4.6 GENERAL DISCUSSION

4.6.1 Review of PNG Oil Palm Field Trials

Despite the fact that P is a very important plant nutrient, oil palm fertiliser trials on the volcanic soils of PNG generally show a lack of response to inorganic P fertiliser applications; even though soil Olsen-P tests are commonly very low (< 10 mg P/kg soil). Considering that palms remove about 25 kg P per hectare per annum readily-available P soil supplies would not be expected to last indefinitely without rapid replenishment from fertiliser sources.

At Hoskins and Kapiura, oil palm field trials have not yet shown any consistent responses to P fertilisers. Field trials indicate that P responses, were either nonsignificant or inconsistent over a number of years and were mostly secondary to nitrogen fertiliser responses. Soils at Hoskins and Kapiura have medium to high PR values (60 - 70%), low pH in NaF (< 10.4) and low Olsen P (5 - 10 mg P/kg soil).

Likewise at Popondetta there are no reports of any significant responses to P fertilisers. Soils at Popondetta have very low PR values (30%), low pH in NaF (< 10.4) and low Olsen P (5 - 10 mg P/kg soil).

The only exception is found in Trial 201 at Bialla. Palms in this trial have shown significant responses to P fertiliser applications in yield, physiological growth parameters and enhanced uptake of nitrogen and magnesium. Soils at Bialla have very high PR (>90%), high pH in NaF (>10.4) and very low Olsen P values (< 4 mg P/kg) down to 60 cm depth.

From the review it can be concluded that for oil palms to respond to P fertilisers PR needs to be > 90% and Olsen P values have to be very low; less than 4 mg/kg.

4.6.2 Soil Characteristics (Chemical and Mineralogical) and Phosphorus Status

4.6.2.1 Mineralogical Properties and Phosphate Retention

All PNG volcanic ash soils in this study are relatively young as judged by the presence of high to very high levels of volcanic glass minerals in the sand, silt and clay fractions. Soil parent materials are dacitic for the Popondetta soils and somewhere between dacitic and andesitic for the soils in Hoskins, Kapiura and Bialla.

West New Britain soils at Hoskins and Kapiura are similar as judged by the similarities in types and amounts of primary and secondary clay minerals. Bialla soils although similar to those at Hoskins and Kapiura seem to be more weathered because of the presence of large amounts of amorphous secondary clay minerals (allophane and ferrihydrite). Soils at Popondetta are different from those in West New Britain and the detailed mineralogy reveals the presence of plant opals and hornblende together with very low levels of allophane.

In this following section, the dominant P characteristics of the soils used are discussed along with the predominant forms of soil P present, as found by fractionation.

4.6.2.1.1 Hoskins and Kapiura

Soils at Hoskins have weathered mostly at the 0 - 10 cm depth judging by the presence of high amounts of amorphous minerals at this depth. Allophane is less abundant at the lower 2 depths. This has resulted in a change in PR from high (60 - 70%) at 0 - 10 cm to low or medium values (30 - 40%) in the lower depths.

Soils at Kapiura seem to have weathered further down to 45 cm as indicated by the presence of high levels of allophane in the clay fraction down to this depth. Correspondingly PR values remain in the medium zone (54 - 66%) at this depth, being slightly lower than at 0 - 10 cm depth at Hoskins and 0 - 45 cm depth at Kapiura.

Forms of P

Total P contents in Hoskins and Kapiura soils is high to very high (>1000 mg/kg) in the top 10 cm with most of the P being in organic forms. Most P at both sites occurs in the 0 - 10 cm depth because of accumulation of plant residues and soil organic matter in this layer.

Readily-available P forms (Resin-Pi and Bicarb.-Pi) account for 1 - 3% of total P. For these two soils, P nutrient cycling and movement seems to be controlled by PR in the 0 - 10 cm depth for Hoskins soils and probably down to 45 cm for Kapiura soils. Oil palm trials at Hoskins did not show any response to P fertilisers possibly because of the extra supplies from the subsoil and even from buried soil horizons that are known to occur in Hoskins area.

4.6.2.1.2 Bialla

Soils at Bialla are more deeply and uniformly-weathered compared to other PNG soils in this study and this has resulted in the formation of high amounts of secondary amorphous clay minerals. This situation leads to very high PR capacities (>90%) and very high pH values in NaF (>10.4) at all depths. It also implies that most of the P in Bialla is retained in forms that are not so readily-available for plant uptake; both in the topsoils and subsoils.

Forms of P

Total P, in Bialla soils, is very high (>1200 mg/kg) and mostly in organic forms (60 - 70%) as indicated by P fractionation. Readily-available forms (Resin-Pi and Bicarb.-Pi) comprise less than 1% of total P. Replenishment of these readily-available P forms seems to be controlled by the very high PR capacity of Bialla soils. At Bialla there seems to be a tight P nutrient cycle which is controlled by the presence of high amounts of allophane and ferrihydrite. These secondary amorphous clay minerals probably complex organic matter which results in immobilisation of P in organic matter and cause inorganic P to be retained strongly in plant unavailable form. This combination of factors is thought to be the reason why the application of P fertilisers in Trial 201 produced measurable P responses. The underlying factor determining P availability for crop uptake in Bialla soils appears to be the presence of high amounts of amorphous clay minerals at all depths.

4.6.2.1.3 Popondetta

Popondetta soils are very young and have very low levels of allophane and ferrihydrite compared to soils in West New Britain Province. The presence of very low levels of secondary amorphous clay minerals translates into low PR values (30%) in this soil.

Forms of P

Total P contents of Popondetta soils are relatively constant at all depths but are lower than those of West New Britain. The major form of P, as indicated by P fractionation, is organic (60% of total as an average for all depths). The readily-available P (Resin-Pi and Bicarb.-Pi) forms account for less than 2% of total P but replenishment must be rapid enough because these Popondetta soils show no field response to P fertilisers.

To summarise, the presence of amorphous minerals explains much of the behaviour of P in the trial soils. The major source of available P in these soils is probably from organic forms. Depletion of this Po form to very low levels may be required before P responses become evident in Hoskins, Kapiura and Popondetta soils.

4.6.3 Comparison of NZ and PNG Soils

Both NZ and PNG volcanic soils have high to very high levels of volcanic glass in the silt and clay fractions in the topsoils. However in the sand fraction, New Zealand soils and the soil from Popondetta have low amounts of volcanic glass whereas the soils of West New Britain have moderate to very high levels. This distinguishes Popondetta soil from those in the Island region (may only be a difference in proximity to source).

The allophane and ferrihydrite contents in the Egmont (NZ) soil are higher than for all PNG soils except Bialla. The allophane contents of the other NZ soils fall within the range of the PNG soils.

PR in the NZ soils is medium to high which is similar to Hoskins and Kapiura soils, but lower than Bialla, and higher than Popondetta.

Taupo and Ramiha soils are more acidic than most of the PNG soils.

Total P in NZ soils is as high as in PNG soils with the major form being organic-P. Bicarb.-Pi (Olsen-P) in Egmont soil is very low and is comparable to nonfertilised PNG soils while Taupo and Ramiha tend to have higher Olsen -P values.

4.6.4 Fate of P Fertilisers in PNG Soils

Fractionation of Hoskins and Kapiura soils showed that most of the P accumulates in the top 10 cm layer with measurable but smaller amounts at lower depths. Most of the P accumulates in the surface layer because of low P solubility which restricts its movement, by leaching, to lower depths. Accumulation at lower depths is probably due to leaching of soluble organic forms or movement of particulate forms through soil pores because of the sandy nature of these soils.

The major sink in which most of the P accumulates is organic. Continuous P applications apparently increase the amount of organic-P but where C and other nutrients are limiting, this pool will reach an equilibrium situation. Of intermediate importance is the pool created by adsorption of P onto surfaces of Al^{3+} and Fe^{3+} oxides and hydroxides as measured by NaOH extraction. This form is not directly available for crop uptake at least in the very short term (Cross and Schlesinger, 1995).

Availability of P in the long term, probably depends on factors that control mineralisation of organic matter and the release of P into soil solution ready for crop uptake. For Hoskins and Kapiura soils, with their medium to high PR, most P should be available for crop uptake but fluctuations in other factors such as the status of other plant nutrients may determine whether the palms will respond to P fertilisers or not. In Bialla soils the major factor determining P availability is undoubtedly PR and P released from organic forms will quickly made unavailable by adsorption onto amorphous clay minerals. For Popondetta soils which have very low PR, P released from organic matter mineralisation is likely to remain readily available for plant uptake.

This study has highlighted the fact that organic matter in the soils is a very important P source and P sink. Any available P from fertilisers that is not taken up by the crops is stored here. For oil palm this pool is very important for meeting the crops long-term P requirements. Work done with cocoa indicated that it was the decrease in organic-P forms that led to responses to P fertilisers (Smith and Acquaye, 1963 and Omotoso, 1971). Therefore the maintenance and monitoring of this pool (NaOH-Po and Bicarb.-Po) will probably be a key factor in oil palm P nutrition in soils with PR levels of 30 - 70% as found at Hoskins, Kapiura and Popondetta. In soils with very high PR (>90%) such as at Bialla, fertiliser applications to increase Pi in the soil solution will probably be an important factor in obtaining higher yields and the direct use of fertiliser will probably take precedence over maintenance of the organic pool.

Using soil test results to predict the long term P requirement of oil palm will be difficult because palm roots can scavenge for P at lower depths, and access P directly from P-bearing minerals and/or from buried soils. There are many other factors that determine P availability such as PR, soil organic matter contents and dynamics, microbial interactions, to mention a few. Factors that influence these factors ultimately determine P availability and soil tests probably only play a minor role.

4.6.4 Categorising Soils for P Responsiveness

From the results of this investigations, the volcanic oil palm producing soils of PNG have been classified into three major groups in relation to soil factors that will most likely control P responsiveness as follows:

1) Soils that are most likely to show large and consistent P responses. These soils will have the following characteristics; very high levels of Feo (≥ 1%), Alo (≥ 2%), very high levels of allophane, very high PR (> 90%), pH in NaF > 10.4 and very low Bicarb.-Pi (<4 mg /kg). The Bialla soils are examples of this type of soil.

2) Soils that will probably show inconsistent responses to P fertilisers for which P fertiliser requirement are probably secondary to nitrogen or which show interactions with nitrogen would be those that have; medium to high Fe_o (0.45 - 1%), Al_o (1 - 1.9%) contents, moderate to high levels of allophane, medium to high PR values (50 - 70%), pH in NaF of 10 - 10.4 and Bicarb.-Pi levels of 4 - 6 mg/kg. Soils at Hoskins and Kapiura would be examples of this general category.

3) Soils not expected to show major P responses would have; low Feo (< 0.45%), low Alo (< 1%), very low contents of allophane, low to medium PR (< 35%), pH in NaF <10 and Bicarb.-Pi of greater than 5 mg/kg. Typical soils in this category would include those at Popondetta.

CHAPTER 5: CONCLUSION AND IMPLICATIONS

Results from this study have indicated that the major soil factor influencing P availability and P uptake by oil palm in PNG volcanic soils appears to be phosphate retention (PR). PR in PNG soils is strongly related to the presence and amounts of amorphous secondary clay minerals (allophane and ferrihydrite). Relative amounts of these 2 minerals depend on the age of volcanic ash soils. Bialla soil which has very high PR (>90% to at least 1 m depth) because of high levels of allophane and ferrihydrite, is the only soil that has shown significant P responses for oil palm. Hoskins and Kapiura soils which have medium to high PR (60 - 70%) in the top 10 - 20 cm, show inconsistent P responses while Popondetta with its very low PR (30%) has not shown any response to P fertilisers; in trials, to date.

PR capacity and Olsen P values can be very useful indicators for assessing potential responses to P fertilisers. Oil palm grown in soils with very high PR (>90%) and Olsen P values of less than 4 mg/kg will most likely respond to P fertilisers. Soils in Bialla area will be included in this group. These Bialla soils are P responsive even though they are relatively deep soils. In soils with medium to high PR (60 - 70%), palms will probably show inconsistent responses to P fertiliser applications and P is most likely will be secondary to N requirements such as N; soils from around Hoskins and in Kapiura will fall into this category. However oil palm grown in soils with low PR (30 - 40%) will not usually respond to P fertilisers and some of the areas in Popondetta will be in this group.

Classifying soils into soil groups according to PR in this way could assist with determining where to set up P fertiliser trials. Because oil palm field fertiliser trials usually run for more than 10 - 15 years and a good scientific basis for site selection is important for the efficient use of research personel and facilities.

In oil palm plantation soils, P characteristics could help determine which parts of the estates are likely to respond to fertilisers and this could be useful for drawing up field manuring budgets. This could change the practice of making blanket recommendations which can result in inefficient use of expensive P fertilisers, on soils that are unlikely to respond to P. The same argument can obviously be extended to smallholder blocks.

Soil PR capacity is related to the anion adsorption capacity of soils and knowledge gained from PR capacity and factors influencing it could also be extended to other anions, such as sulphate. One can more or less expect the same pattern of responses to S as occur for P in the volcanic soils; however S is probably even less important in oil palm production than P at this time.

Results from this study have shown that, in PNG topsoils, more than 50% of P is typically present in organic forms. It seems that in deep Bialla soils where there is very high PR and also very high organic matter and organic P levels, the P supply is still not adequate to meet total crop requirements of oil palm. Thus the high organic P levels in Bialla soils does not itself guarantee that sufficient P is available for uptake and palms grown in these soils will normally require P from extraneous sources, such as inorganic P fertilisers, to meet their present and future requirements.

The above situation does not hold for Hoskins and Kapiura soils because in addition to surficial supplies of P, an extra contribution is made from deeper in the profile depths probably from buried soil horizons.

Organic forms of P are not only a major potential source of P but also a major sink. In P-fertilised soils, at Hoskins and Kapiura, most of the P (70 - 80%) accumulates, in the surface soil layers, in this organic P fraction. It seems that P movement in the P nutrient cycle in these 2 soils is slowed down by incorporation into organic forms in the top 10 cm soil layer and probably will not be readily-available for plant uptake because of the medium to high PR capacity. Even if P is not readily available, palms at these 2 sites probably still have access to P supplies from lower depths; perhaps where PR is lower and/or where buried soils occur. This implies that for oil palm, or any other tree crop with a deep rooting system, consideration of soil profile characteristics is important in assessing overall nutrient supply. The higher levels of amorphous clay minerals at all depths in soils at Bialla, compared with those at Hoskins and Kapiura, is one of the reasons why Bialla soils are more responsive to P fertilisers.

Maintenance of high organic matter levels in the soils is then very important in conserving P for oil palm crops. Agronomic practices that lead to any reduction in the amount of soil organic matter will also reduce long term P supplies for the crop. However, as we have shown, organic matter accumulates more in soils with high amounts of amorphous clay minerals yet these soils can still present short-term deficiencies of P. So this is somewhat an enigma.

Further work is required to quantify the distribution and fluxes of P, as well as other nutrients, between different pools in order to help draw complete nutrient budgets for the different oil palm growing soils. An understanding of nutrient fluxes will form the basis of fertiliser recommendations along with results of fertiliser field trials. With P it can be seen that the major source/sink is organic but P availability appears to be determined by the soil PR characteristics. Nothing is known about the dynamics of the organic P pool.

What is missing is information on the nett mineralisation rates of organic matter and the availability of this released P to oil palm. Under tropical conditions, rates of mineralisation are probably related to PR. Studying mineralisation rates of organic matter could help provide information on availability of P in the short, as well as long term. This information is also very important for soils with low to medium PR because knowing when the palms might start responding to P fertilisers is important.

Soil tests using conventional methods alone (e.g. Olsen P) may not be useful for oil palm production because as is reviewed in this study, even where Olsen P levels were very low (<10 mg /kg), PNG palms show a lack of response to P fertilisers. Soil mineralogical and chemical (PR) characteristics have to be taken into consideration as well when determining oil palm P requirements. It turns out, from this study that the Bicarb.-Po fraction extracted by the Olsen reagent probably needs further testing in relation to oil palm growth and P responses. It seems in PNG situations that replenishment of soil solution-P from the extractable organic pool, may be important in meeting the crop requirements for P.

Relationships between plant tissue analysis and palm responses to P also need further evaluation. Despite P levels being lower than 0.150% DM (0.140 - 0.150% DM range), oil palm grown in PNG generally have high yields (>25 tonnes/ha/year for mature palms) and do not respond to P fertilisers. At Bialla, where palms do respond to P fertilisers, yields are <20 tonnes/ha/year and leaf P levels are <0.138% DM . This probably indicates that critical leaf P concentration for oil palm grown under PNG conditions could be lower than in Malaysia i.e. within the range 0.140 - 0.148% DM. The critical levels and sufficiency range for P as well as other nutrients certainly need to be established for PNG conditions and for both volcanic and nonvolcanic soils.

Other areas worthy of study on the P nutrition of oil palm in PNG include microbial interactions at soil/root interface (e.g. mycorrhizae) which could assist palms by improving the efficiency of P uptake.

Finally it appears that the mineralogical and P sorption characteristics of young volcanic ash soils in NZ are sufficiently similar to those in PNG to provide useful information on the potential effectiveness of P fertilisers and residual effects. Hence some knowledge on the chemistry of NZ volcanic soils can be translated into PNG environment to assist in understanding the dynamics of P in oil palm plantations. This is despite the major differences in environmental conditions between NZ and PNG, but is made possible by the relative young age if the PNG oil palm growing volcanic soils which can contain abundant supplies of highly reactive allophane and ferrihydrite clay minerals.

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Appendix 1

Location: Trial 107 Bebere Plantations, Hoskins

Parent Materials : Volcanic Alluvial/Colluvial Materials

Slope: 0 - 1°

Elevation: 7 m

Topography: Flat alluvial plain

Drainage: Well drained

Vegetation: Replanted Oil Palm Plantation

Climate: Humid tropical climate with 26 C mean temperature, rainfall >3500 mm / year

Profile	Depth (cm)	Description
Ao	0 - 15	Black (10 YR 2/1) sandy loam: friable, slightly sticky and nonplastic: moderately developed with fine subangular blocky structure: many fine and few medium roots: field pH 6.5 clear boundary to
Ae	15 - 35	Olive brown (2.5 Y 4/4) loamy sand: very friable to loose, nonsticky and nonplastic: weakly developed with fine to medium granular structure: few medium and common coarse roots: field pH 6.8: clear boundary to

Appendix 1 continued

B1	35 - 47	Dark yellowish brown (10 YR 3/4) loamy sand: very friable, nonsticky and nonplastic: weakly developed with fine granular structure: few medium roots: field pH 6.7: diffuse boundary to
B2	47 - 70	Dark yellowish brown (10 YR 4/4) sandy clay loam: friable, slightly sticky and slightly plastic: moderately developed with fine subangular blocky structure: few medium roots: field pH 6.0: diffuse boundary to
B2	70 - 90	Yellow brown (10 YR 5/6) granular loam: friable, slightly sticky and nonplastic: weakly developed with medium granular structure: few medium roots: field pH 6.6: diffuse boundary to
B3	90 - 100	Yellow brown (10 YR 5/8) sandy clay loam: friable, slightly sticky and slightly plastic: moderately developed with medium subangular blocky structure: few medium and common coarse roots: field pH 6.5: diffuse boundary to
Bc	100 - 125	Olive yellow (2.5 Y 6/6) sandy clay loam with common, medium, distinct and light brownish gray (2.5 Y 6/2) mottles: friable, slightly sticky and nonplastic: weakly developed with medium subangular blocky structure: few medium and common coarse roots: field pH 6.6: clear wavy boundary to
Bc	125 - 175	Light gray (2.5 Y 7/2) Pumice gravel with field pH of 6.5 and clear boundary to
Bh	175 - 190	Olive brown (10 YR 4/4) sandy loam: friable to loose, nonsticky and nonplastic: weakly developed with medium

appendix 1 continued

		subangular blocky to granular structure: field pH 6.5: distinct boundary to
BC	190 - 200	Olive yellow (2.5 Y 6/6) loamy sand: friable to loose, nonsticky and nonplastic: weakly developed with medium granular structure: few coarse roots: field pH 6.0

Appendix 2

Soil Description

Location : Trial 402, Bilomi, Kapiura Plantations

Parent Material: Alluvial volcanic ash

Slope: 1°

Elevation: 7 m

Topography: Flat alluvial plain

Drainage: Well drained

Vegetation: Oil Palm Plantation, palms planted at density of 110 palms / ha from virgin tropical rainforest.

Climate: Humid tropical climate with 26 C mean temperature, rainfall > 3500 mm / year.

Profile Depth (cm)	Description
0 - 10	Very dark brown (10 YR 2/2) sandy loam: friable, non plastic and slightly sticky: weakly developed with fine subangular blocky structure: has many fine roots: field pH 6.0: diffuse boundary to
10 - 23	Very dark brown (10 YR 2/2) sandy loam: friable, nonplastic and slightly sticky: weakly developed, fine granular to subangular blocky structure: few fine roots: field pH 6.0: clear

Appendix 2 continued

	boundary to
23 - 45	Light reddish Brown (2.5 Y 6/4) loamy sand: friable, nonsticky, and nonplastic: weakly developed with fine granular structure: few medium roots: field pH 6.0: clear boundary to
45 - 70	Dark yellowish brown (10 YR 3/6) loamy sand: friable, nonsticky and nonplastic: weakly developed with fine granular structure: common medium and few coarse roots: field pH 6.5: clear boundary
70 - 105	Yellowish brown (10 YR 5/8) granular loam: friable, nonsticky and nonplastic: weakly developed with fine granular structure: few medium and coarse roots: field pH 6.6: clear boundary to
105 - 133	Gray (2.5 Y 5/0) loamy sand: friable, nonsticky and nonplastic weakly developed: fine granular structure: very few fine roots: field pH 6.2: clear boundary to
133 - 138	Light yellowish brown (2.5 Y 6/4) loamy sand: friable, nonsticky and nonplastic: weakly developed with fine granular structure: very few fine roots: field pH 6.5: clear boundary to
138 - 145	Light gray (10 YR 7/2) coarse sand: friable, nonsticky and nonplastic: weakly developed with fine granular structure: no roots: field pH 6.8: clear boundary to
145 - 200	Light gray (10 YR 7/2) pumice gravel with few roots

Comments: Hardpan layer at 133 - 138 cm depth and distinct pumice gravel layer at 2 m depth.

Appendix 3

Location : Trial 205 Kerakera, Bialla Plantation

Parent Material: Colluvial/Alluvial volcanic ash materials

Slope: 2 - 3°

Topography: Flat alluvial plain

Drainage: Well Drained

Vegetation: Oil Palm Plantation

Climate: Humid tropical climate with 26 °C mean temperature, rainfall >3500 mm / year.

Profile Depth (cm)	Description
0 - 15	Black (10 YR 2/1) loamy sand: very friable to loose, nonsticky and nonplastic: weakly developed with fine granular structure: many fine and medium roots: field pH 6.0: diffuse boundary to
15 - 40	Very dark grayish brown (10 YR 3/2) loamy sand: very friable to loose, nonsticky and nonplastic: weakly developed with fine granular: common fine and medium and few coarse roots: field pH 6.0: clear boundary to
40 - 70	Dark brown (10 YR 3/3) silty loam with few, medium, prominent and dark red (2.5 YR 3/6) mottles, slightly sticky, and nonplastic: moderately developed with medium subangular

Appendix 3 continued

	blocky to granular structure: few fine and coarse roots: field pH 6.0: clear boundary to
70 - 170	Dark brown (10 YR 4/3) sandy clay loam with many, medium, prominent and dark red (2.5 YR 3/6) mottles: friable, slightly sticky and slightly plastic: moderately developed with medium subangular blocky structure: few coarse roots: field pH 6.0: diffuse boundary to
170 - 200	Dark yellowish brown (10 YR 4/4) sandy clay loam with strong brown (7.5 YR 5/6) mottles: friable, slightly sticky and slightly plastic: moderately developed with fine subangular blocky structure: field pH 6.0

Comments: High clay content with presence of mottles in the profile.

Appendix 4

Representative Profile: Popondetta

Family: Higaturu

Representative Profile Arehe Pit 3

Location: Block 77E

Parent Material: weathered volcanic ash

Landform Middle terrace

Drainage class : Well drained and rapidly permeable

Profile Depth (cm)	Description
0 - 30	Black (10 YR 2/1) loam to fine sandy clay loam: friable wet plastic and slightly sticky: moderate, fine subangular blocky: many roots: field pH 5.7: smooth clear boundary to
30 - 56	Very dark brown (10 YR 2/2) light sandy clay: firm wet plastic and sticky: weak coarse angular blocky: common roots: field pH 6.5: smooth gradual boundary to
56 - 120+	Dark brown (10 YR 3/3) light sandy clay: firm, wet plastic and sticky: massive: fine roots: field pH 6.8

Appendix 4 continued

Depth (cm)		0 - 30	30 - 70
pH (H_O 1:2.5)		6.5	7.3
Bulk Density (g/ml)		0.95	0.98
Chloride (mg/g)		<12	-
Extractable Cations	Ca	10.6	9.8
	Mg	0.73	1.21
	Na	0.08	0.17
	K	0.17	0.29
Total Exchangeable bases		11.58	11.47
Cation Exchangeable Capacity (CEC)		14	12
Base Saturation (%)		83	96
Reserve Mg (ml/100g)		14.1	28.6
Organic Matter (%)		3.5	0.6
Nitrogen (Total) (%)		0.19	0
C/N ratio		11	-
Available N (kg/ha)		130	14
Acid extractable P (mg/kg)		3	3
P retention (%)		27	37
Extractable S (mg/kg)		<5	-
Extractable boron (mg/kg)		0.52	-
Extractable manganese (mg/kg)		20	-
Particle size Distribution			
	Sand	55	41
	Silt	27	25
	Clay	18	34

Appendix 5

Trials Soil Analysis Results - 1990

Trial	Depth	pH	Extractable Bases (me%)				CEC	BS	Olsen P	P Retention	pH in	Organic C	Total N	C/N	PSDA* (%)		
	(cm)		Ca	Mg	K	Na	(me%)	(%)	(mg/kg)	(%)	NaF	(%)	(%)	ratio	Sand	Silt	Clay
Hoskins																	
107	0 - 20	6.3	4.70	0.46	0.19	0.13	8.0	69	4.7	53	9.7	1.73	0.18	10	52	35	13
	40 - 60	6.6	7.90	0.92	1.88	0.40	13.2	84	4.7	40	8.8	0.65	0.07	9	54	20	27
108	0 - 20	6.4	5.00	0.27	0.58	0.28	9.3	66	2.7	67	9.8	1.34	0.15	9	52	35	13
	40 - 60	6.4	5.10	0.24	0.61	0.38	9.9	64	2.8	65	9.9	1.27	0.13	10	54	35	11
110	0 - 20	6.3	3.50	0.27	0.22	0.11	6.3	65	2.5	51	9.8	1.30	0.13	10	54	35	11
	40 - 60	6.5	5.90	0.53	1.44	0.34	10.4	79	2.7	49	9.4	0.80	0.09	10	62	23	15
117	0 - 20	6.1	3.50	0.17	0.38	0.07	6.2	66	2.9	53	10.0	1.31	0.15	9	53	38	9
	40 - 60	6.3	5.80	0.35	0.78	0.58	10.9	69	4.4	62	9.8	1.09	0.12	10	55	36	10
118	0 - 20	5.9	4.90	0.25	0.34	0.06	7.2	77	3.3	57	9.9	1.68	0.19	9	52	38	10
	40 - 60	6.2	5.50	0.35	0.93	0.39	8.9	81	5.3	52	9.6	0.81	0.09	9	62	23	15
119	0 - 20	6.1	3.90	0.39	0.18	0.09	6.3	72	3.6	56	9.7	1.35	0.13	10	46	38	16
	40 - 60	6.0	3.40	0.26	0.15	0.08	5.1	76	3.5	49	9.8	0.84	0.10	8	49	37	14
120	0 - 20	6.0	7.90	0.60	0.77	0.22	10.7	89	9.7	26	8.7	1.87	0.17	12	69	17	14
	40 - 60	6.5	3.10	0.36	0.84	0.14	5.4	82	6.0	17	8.8	0.24	0.02	12	82	10	9

Appendix 5 continued

Trial	Depth (cm)	pH	Extractable Bases (me%)				CEC (me%)	BS (%)	Olsen P (mg/kg)	P Retention (%)	pH in NaF	Organic C (%)	Total N (%)	C/N ratio	PSDA (%)		
			Ca	Mg	K	Na									Sand	Silt	Clay
Bialla																	
201	0 - 20	5.9	10.5	0.74	0.10	0.06	18.2	63	3.0	92	10.5	4.95	0.53	9	43	37	20
	40 - 60	6.3	4.30	0.28	0.07	0.06	10.1	47	1.4	92	10.4	1.41	0.17	8	44	39	17
Kapiura																	
402	0 - 20	6.2	18.5	3.17	0.63	0.08	24.3	92	2.4	52	9.3	2.16	0.22	10	40	35	25
	40 - 60	6.1	16.4	3.20	0.52	0.12	36.4	55	4.1	42	8.7				47	27	27
Popondetta																	
305	0 - 20	6.2	9.3	0.94	0.13	0.02	11.0	94	7.0	22	8.2	2.02	0.21	10	58	22	20
	40 - 60	6.4	8.8	2.13	0.24	0.11	11.8	96	6.3	47	8.9	0.54	0.06	10	44	14	42
306	0 - 20	6.2	10.1	2.63	0.11	0.03	12.9	99	10.1	17	7.8	1.97	0.19	10	57	28	15
	40 - 60	6.3	2.9	1.70	0.16	0.12	4.2	100	4.3	6	7.5	0.14	0.02	7	83	10	7
309	0 - 20	6.0	4.6	1.24	0.37	0.04	14.5	43	8.6	50	NA	3.10	0.26	12	65	24	11
	40 - 60	6.2	0.9	0.21	0.10	0.03	3.1	40	4.3	12	NA	0.15	0.02	7	81	13	6

Appendix 5 continued

Trial	Depth (cm)	pH	Extractable Bases (me%)				CEC (me%)	BS (%)	Olsen P (mg/kg)	P Retention (%)	pH in NaF	Organic C (%)	Total N (%)	C/N ratio	PSDA (%)		
			Ca	Mg	K	Na									Sand	Silt	Clay
310	0 - 20	6.3	9.5	1.72	0.16	0.04	13.0	88	12.6	28	NA	2.10	0.21	10	62	23	16
	40 - 60	6.5	1.8	0.95	0.08	0.02	3.2	89	5.4	9	NA	0.15	0.02	7	81	13	6
311	0 - 20	6.0	7.2	1.20	0.43	0.03	11.4	78	6.5	27	NA	1.98	0.22	9	63	20	17
	40 - 60	6.2	7.6	1.83	0.28	0.09	11.2	88	5.9	41	NA	0.42	0.05	8	49	10	41
312	0 - 20	6.1	8.0	2.23	0.62	0.03	13.1	83	10.0	40	9.1	2.82	0.26	11	58	36	6
	40 - 60	6.3	2.2	0.75	0.24	0.03	3.6	89	4.4	12	8.0	0.22	0.03	9	72	25	3

* Particle size distribution analysis

Appendix 6

Sand and Silt Fraction Minerals

		Sand Fractions					Silt Fraction				
Sample	Depth (cm)	Volcanic Glass/Plant Opals	Heavy Minerals	Feldspars	Quartz		Feldspars	Cristobolite	Quartz	Kandites	Volcanic Glass
Hoskins	0 - 15	*****	**	****	*		**	*			*****
(107)	15 - 35	*****	**	****	*		*	*			*****
	35 - 70	*****	**	****	*		**	*	*		*****
	70 - 100	****	***	****	*		**	*		***	*****
	100 - 175	*****	***	****	*		**	*	*	***	*****
	175 - 200	*****	**	****	*		*	*	*		*****
Kapiura	0 - 10	****	***	****	*		***	*	*		*****
(402)	10 - 23	*****	***	****	*		**	*	*		*****
	23 - 45	*****	**	****	*		*	*	*	***	*****
	45 - 70	*****	**	***	*		**	*	*	**	*****
	70 - 105	*****	**	***	*		*	*	*	*	*****
	105 - 133	*****	***	***	*		mostly glass	mostly glass	mostly	mostly	*****
	133 - 200	*****	***	***	*		mostly glass	mostly glass	glass	glass	*****

Appendix 6 continued

		Sand Fractions					Silt Fraction				
Sample	Depth (cm)	Volcanic Glass/Plant Opals	Heavy Minerals	Feldspars	Quartz		Feldspars	Cristobolite	Quartz	Kandites	Volcanic Glass
Bialla	0 - 15	***	***	*****	*		***	*	*		*****
(205)	15 - 40	***	****	*****	*		***	*	*		*****
	40 - 70	***	***	*****	*		**	*	*		*****
	70 -170	***	****	****	*		**	*	*	***	*****
	170 - 200	****	****	****	*		**	*	*	***	*****
(201)	0 - 10	***	***	*****	*		***	***	*		*****
	10 - 20	***	***	*****	*		***	***	*		*****
	20 - 30	***	***	*****	*		***	***	*		*****
Popondetta	0 - 10	**	****	****	*		**	***	***	HB	***** #
(323)	10 - 20	* #	****	****	*		**	***	***	HB	***** #
	20 - 30	*	****	****	*		**	***	***	HB	***** #

Appendix 6 continued

		Sand Fractions					Silt Fraction				
Sample	Depth (cm)	Volcanic Glass/Plant Opals	Heavy Minerals	Feldspars	Quartz		Feldspars	Cristobolite	Quartz	Kandites	Volcanic Glass
Egmont	0 - 10	**	****	****	**		***	*	**		*****
Taupo	0 - 10	**	*	***	*		*	*	*		*****
Ramiha	0 - 10	**	**	*****	***		***	*	****		

# = Plant opals present
HB = Hornblende Note hornblende is not a kandite
Volcanic glass on the Mainland had yellow-orange colour due to iron coatings indicating highly weathered materials.
Volcanic glass in WNB soils on the Island were rhyolitic, clear and smaller in structure than Taupo materials.

* = 0 - 5% very low
** = 5 - 10% low
*** = 10 - 25% moderate
**** = 25 - 50% high
***** = >50% very high

Appendix 7

Table Heavy Minerals

Sample	Depth (cm)	Hypersthene	Augite	Magnetite	Ileminite	Hornblende
Hoskins	0 - 15	***	***	*****		
(107)	15 - 35	***	***	*****		
	35 - 70	***	***	*****		
	70 - 100	***	***	*****		
	100 - 175	***	***	*****		
	175 - 200	***	***	*****		
Kapiura	0 - 10	****	****	****		
(402)	10 - 23	****	***	****		
	23 - 45	***	****	****		
	45 - 70	***	****	****		
	70 - 105	****	***	****		
	105 - 133	***	***	*****		
	133 - 200	***	****	****		
Bialla	0 - 15	****	****	****		
(205)	15 - 40	****	****	****		
	40 - 70	****	****	****		
	70 -170	*****	****	***		
	170 - 200	*****	****	***		
(201)	0 - 10	****	***	****		
	10 - 20	****	***	****		
	20 - 30	****	****	****		
Popondetta	0 - 10			**		*****
(323)	10 - 20			***		*****
	20 - 30			***		*****
Egmont	0 - 10	***	****	****	*	***
Taupo	0 - 10	*****	***	****		
Ramiha	0 - 10	***	****	****		***

* = 0 - 5 % very low
** = 5 - 10% low
*** = 10 - 25% moderate
**** = 25 - 50% high
***** = >50% very high

Appendix 8

Acid Oxalate and Sodium Pyrophosphate Al, Fe and Si Extracts

			Acid Oxalate				Na Pyrophosphate				
Site	Sample	Depth (cm)	Al %	Fe %	Si %		Al%	Fe %	Al/Si Ratio	Ferrihydrite %	Allophane %
Hoskins	107NP	0 - 10	1.33	0.6	0.5		0.35	0.24	2.04	1	4
	107HP	0 - 10	1.48	0.66	0.52		0.49	0.33	1.98	1	4
	Profile	0 - 15	1.91	0.73	0.63		0.6	0.39	2.16	1	5
		15 - 35	0.64	0.27	0.38		0.05	0	1.62	0.5	2
		35 - 70	0.5	0.86	0.23		0.02	0.07	2.17	1	2
		70 - 100	1.09	0.92	0.72		0.04	0.04	1.52	2	4
		100 - 175	1.36	1.37	0.84		0.02	0.05	1.66	2	5
		175 - 200	0.58	0.35	0.28		0	0.01	2.20	0.4	2
Kapiura	402NP	0 - 10	0.99	0.67	0.3		0.41	0.41	2.01	1	2
	402HP	0 - 10	1.18	0.69	0.37		0.38	0.41	2.25	1	3
	Profile	0 - 10	1.57	0.79	0.57		0.4	0.39	2.14	1	4
		10 - 23	2.25	0.88	1.12		0.18	0.12	1.92	2	8
		23 - 45	1.24	0.58	0.85		0	0.03	1.52	1	5
		45 - 70	0.16	0.3	0.08		0	0.02	2.08	0.5	1
		70 - 105	0.03	0.09	0.03		0	0.01	1.04	0.2	0.2
		105 - 133	0.02	0.04	0		0	0.01	0	0.1	0
		133 - 200	0.06	0.04	0		0	0.01	0	0.1	0

Appendix 8 continued

			Acid Oxalate				Na Pyrophosphate				
Site	Sample	Depth (cm)	Al %	Fe %	Si %		Al%	Fe %	Al/Si Ratio	Ferrihydrite %	Allophane %
Bialla	205NP	0 - 10	2.75	1.34	1.16		0.62	0.51	1.91	2	9
	205HP	0 - 10	2.77	1.41	1.24		0.61	0.51	1.91	2	9
	Profile	0 - 15	3.02	1.5	1.32		0.69	0.55	1.84	3	10
	(205)	15 - 40	4.42	1.85	2.49		0.43	0..21	1.67	3	19
		40 - 70	6.23	2.22	3.6		0.32	0.08	1.71	4	27
		70 - 170	6.79	2.35	3.84		0.25	0.09	1.74	4	29
		170 - 200	5.96	1.94	3.25		0.2	0.09	1.85	3	24
Bialla	201	0 - 10	3.15	1.37	1.38		0.59	0.53	1.93	2	10
		10 - 20	3.6	1.43	1.64		0.4	0.3	2.03	2	12
		20 - 30	3.37	1.21	1.76		0.27	0.14	1.83	2	13
Popondetta	323	0 - 10	0.26	0.45	0.06		0.17	0.35	1.56	0.8	0.4
		10 - 20	0.25	0.45	0.03		0.17	0.32	2.78	0.8	0.4
		20 - 30	0.28	0.44	0.09		0.14	0.28	1.62	0.8	0.5
NZ Soils	Egmont	0 - 10	2.43	0.72	0.94		0.2	0.14	2.47	1	9
	Taupo	0 - 10	1.1	0.34	0.35		0.2	0.27	2.68	0.6	3
	Ramiha	0 - 10	0.94	0.94	0.15		0.55	0.94	2.71	0.3	1

Appendix 9

Soil Chemical Results

Site	Sample	Depth (cm)	P retention %	pH (1:2.5 H_2O)	pH 1M KCl	pH change	pH 1M NaF
Hoskins	107 NP	0 - 10	62	6.4	5.2	-1.2	10.3
		10 - 20	42	6.5	5.4	-1.1	10.3
		20 - 30	34	6.6	5.4	-1.2	10.1
	107 HP	0 - 10	68	6.1	5.1	-1	10.4
		10 - 20	49	6.4	5.4	-1	10.3
		20 - 30	33	6.6	5.4	-1.2	10.1
	Profile	0 - 15	73	6.2			10.5
		15 - 35	35	6.4			10.3
		35 - 70	44	6.5			9.6
		70 - 100	59	6.5			9.9
		100 - 175	69	6.5			9.9
		175 - 200	32	6.5			9.5
Kapiura	402 NP	0 - 10	62	5.9	4.9	-1	10.1
		10 - 20	53	6.3	5.3	-1	10.1
		20 - 30	44	6.5	5.3	-1.2	10.1
	402 HP	0 - 10	61	5.9	5.1	-0.8	10.2
		10 - 20	62	6.4	5.4	-1	10.5
		20 - 30	55	6.5	5.5	-1	10.4
	Profile	0 - 10	66	6.1			10.2
		10 --23	53	6.5			10.5
		23 - 45	54	6.7			10.1
		45 - 70	27	7			9.4
		70 - 105	12	7.2			8.8
		105 - 133	12	7.2			8.6
		133 - 200	8	7.1			8.8
Bialla	205 NP	0 - 10	87	6.1	5.3	-0.8	10.3
		10 - 20	93	6.3	5.4	-0.9	10.8
		20 - 30	96	6.2	5.4	-0.8	10.8
	205 HP	0 - 10	93	6	5.2	-0.8	10.6
		10 - 20	95	6.2	5.3	-0.9	10.8
		20 - 30	97	6.3	5.4	-0.9	10.9

Appendix 9 continued

Site	Sample	Depth (cm)	P retention %	pH (1:2.5 H_2O)	pH 1M KCl	pH change	pH 1M NaF
Bialla 205	Profile	0 - 15	90	6.4			10.5
		15 - 40	97	6.5			10.9
		40 - 70	97	6.5			11
		70 - 170	97	6.3			10.7
		170 - 200	96	6.4			10.5
	201	0 - 10	94	6.1	5.2	-0.9	11
		10 - 20	95	6.2	5.4	-0.8	11
		20 - 30	94	6.3	5.6	-0.7	11
Popondetta	323	0 - 10	31	6.3	5.6	-0.7	8.8
		10 - 20	31	5.3	4.3	-1	9
		20 - 30	33	5.5	4.6	-0.9	9.2
NZ Soils	Egmont	0 - 10	69	6.7	5.8	-0.9	10.3
	Taupo	0 - 10	55	4.3	4.2	-0.1	10.6
	Ramiha	0 - 10	65	4.9	4	-0.9	10