A REVIEW OF PROPERTIES, NUTRIENT SUPPLY, CULTIVATION AND MANAGEMENT OF VOLCANIC SOILS, WITH PARTICULAR REFERENCE TO PAPUA NEW GUINEA.

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ABSTRACT

Soils derived from volcanic ash are called andisols. Andisols have good physical properties and are able to resist erosion because of the stable nature of dominant clay minerals such as allophane in them. However, they have a poor ability to supply nutrients. The dominance of allophane, allophane - organic matter complexes, and dependency of cation and anion exchange mechanism on soil pH contribute to the poor chemical fertility of volcanic ash soils. Such features give peculiar characteristics to andisols and make their management difficult.

Intensive weathering of the ash on volcanic soils has resulted in losses of Si and bases. Si may combine with Al or Fe to form allophane, imogolite, gibbsite or halloysite, depending on the stage of weathering and prevailing climates. These clay minerals form complex associations with organic matter, and together they influence the charge characteristics of andisols.

The review of research on this soil type indicates that the principle constraints to agricultural production are likely to be imposed by chemical properties. The specific chemical problems of weathered andisols are high P-fixation, low pH, low available K, Mg, Ca, low BS(%), low ECEC, deficient B, Mo, Zn and suboptimal levels of Mn, Cu and Fe. The evidence is overwhelming that the management of organic matter is the key to sustaining agriculture on this soil type. It results in increasing the magnitude of the negative charged sites, enhances the ECEC, supplies a wide range of macro and micro nutrients, as well as maintaining the soil physical and chemical fertility. The review identifies pitfalls in the management of andisols and discusses practical and cost effective ways of tackling them.

Keywords: *Papua New Guinea, Andisols, Volcanic ash soils, Organic matter, Soil fertility management*

A. PROPERTIES AND NUTRIENT SUPPLY IN VOLCANIC SOILS

1.0 INTRODUCTION

A comprehensive review of research on Central American volcanic soils going back to the 1960s was carried out by Sanchez (1973). Since that review there have been quite significant advances in the understanding of the chemistry and behavior of this soil type. A significant development has been the advancement in the classification of this soil type, previously within the Order inceptisols (Sub order andepts), to the Order andisols (Wada 1985).

The bibliography shows that many scientific man years of research have been invested in the study of the chemistry of this soil type but little of this information has been translated to appropriate management practices. Therefore it has been the aim of this work to review research conducted so far on this soil type with the objective of deriving management practices relevant and suited to Papua New Guinea (PNG) where a significant proportion of cultivated soils are derived from volcanic ash.

2.0 THE VOLCANIC ASH SOILS OF THE TROPICS

The soil is the basic resource base of farmers everywhere. Constraints to food production in the tropics maybe imposed by climatic conditions, or maybe due to inherent soil and management

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problems. Ash derived soils are reported not only to sustain some of the tropics most productive and stable agricultural systems, but also support heavy densities of human and animal populations (Oades *et al.* 1989). The capacity of these soils to supply nutrients for sustainable agriculture seems to differ amongst different ash derived soil types. It is essential that constraints and/or beneficial attributes of andisols are reliably identified and understood if optimum and sustainable production is to be obtained from them.

2.1 Soil Taxonomy

Ten Soil Orders were proposed and used in the USDA soil classification system. Soils derived from volcanic ash are known as andisols, and these until the 1980s were within the Order inceptisols (Suborder andepts). Recent developments in soil classification have led to raising andepts to Order level of andisol (Wada 1985). Hereafter, andisol is used to encompass Great Group soils of volcanic origin currently under inceptisols because the andisol nomenclature at Great Group level has not been formally ratified. Andisols and volcanic ash soils (VAS) are used interchangeably throughout this report.

2.2 Distribution of Andisols in the Tropics

Andisols are associated with volcanic eruptions which occurred many thousands of years ago. Each has a localised distribution but overall they are geographically widespread throughout the world (Fig. 1). Their generalised area distribution relative to other major tropical soils is given in Table 1. Andisols occupy 43 million hectares (ie. 0.86%) of total tropical soils (Table 1), and about 124 million hectares (0.84%) of the world land surface (Leamy *et al.* 1981).

A significant proportion of cultivated soils of tropical America, the Caribbean, Columbia, Peru, Ecuador, Bolivia, Japan, PNG, New Zealand and Indonesia are derived from volcanic ash. A review of the distribution of andisols in other parts of the world is given elsewhere (Leamy *et al.* 1981). The distinctive properties of different types of ash derived soils are primarily a function of the climates under which the soil is formed. VAS of the drier tropics differ in parent materials and geologic age, and are formed under extreme climates than those of the humid tropics (Wada 1985; Mitzota & Chappelle 1988).

2.3 Distribution of Andisols in PNG

Figure 2 shows the distribution of andisols in PNG. This soil commonly occurs in association with other major soil types (Bleeker 1983). The following distributional grouping maybe generally made at the soil Great Group level.

Andaquepts

Andaquepts are volcanic soils formed under poorly drained conditions which have limited landuse potential. They are also relatively rare in occurrence but are found in a wide variety of climates and at altitudes from sea level to 2000 m. In the highlands this soil may be associated with hydrandepts and on the lowlands they may grade into both eutrandepts and dystrandepts (Bleeker 1983).

Vitrandepts and Durandepts

These are typically lowland soils near active volcanoes. They are in their early stages of soil formation and are least weathered, dominant in sand, weakly acid, and with bulk densities higher than 0.8g cm^{-3} (Wada 1985). Vitrandepts occur extensively on Northern, New Ireland, New Britain and Madang provinces (Karkar Island). These soils are highly susceptible to erosion. Durandepts have a limited distribution on New Guinea mainland and coastal areas (e.g Madang province).

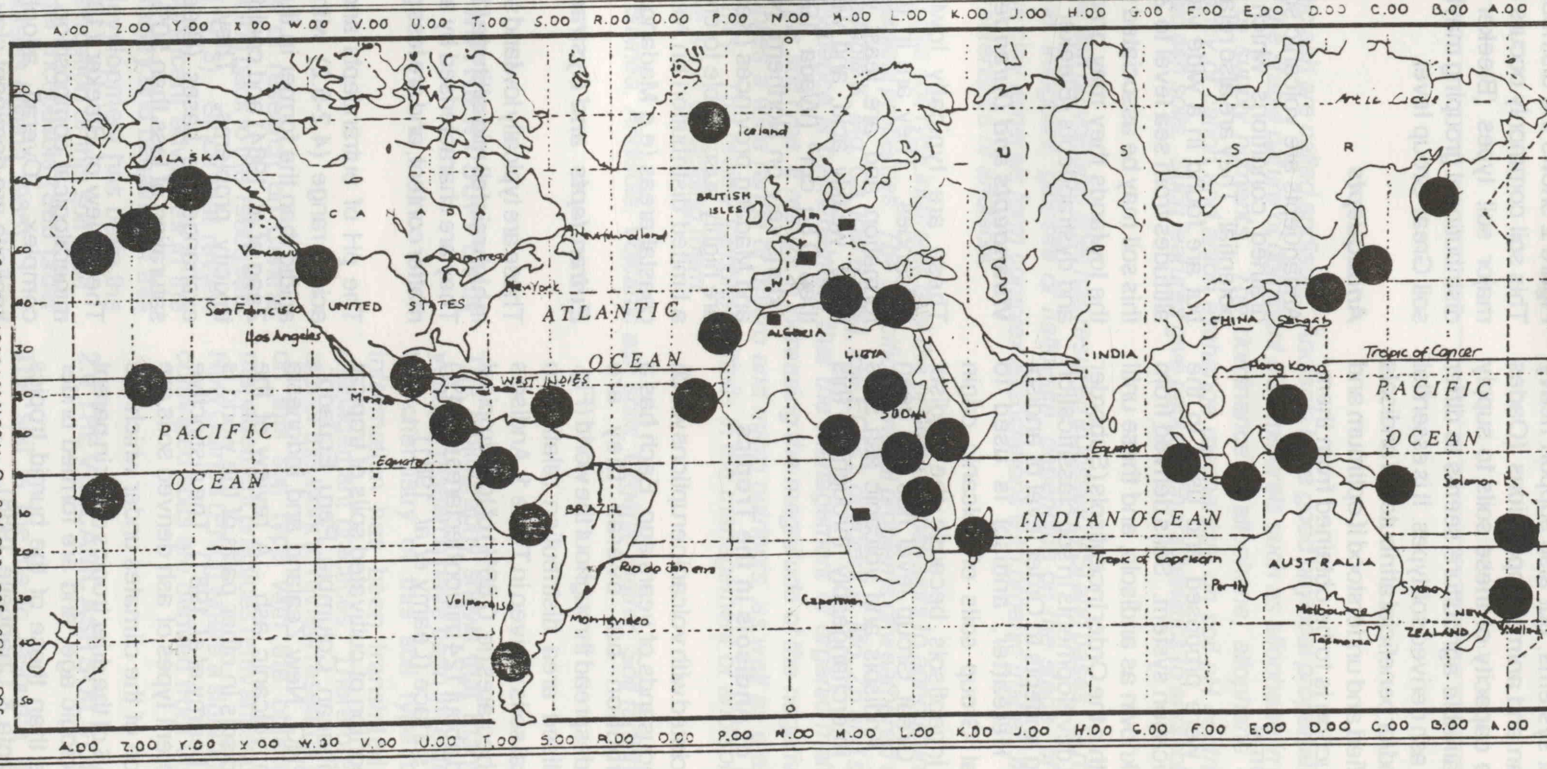
Eutrandepts and Dystrandepts

These are typically lowland soils but occur extensively in high rainfall mid-altitude (1200-1500 m.a.s.l) areas. They are characterised by a medium to high organic matter content, and are less gravelly than vitrandepts.

The pH of eutrandepts and dystrandepts is in the acidic range (4.2-5.2) with the latter being more acidic than the former in the upper profiles (Vander Zaag *et al.* 1984) and could pose serious Al and Mn toxicity problems. They have low to moderate exchangeable bases (Bleeker 1983) and a base saturation of less than 50% (Wada 1985).

The review of Bleeker (1983) shows that the clay mineralogical composition of these soils are quite complex. Overall, allophane, halloysite and/or kaolinite are dominant clay minerals with low levels of gibbsite. These soils occur mainly on Bougainville, New Britain and Northern province in the lowlands,

Figure 1. **Map of the worldwide distribution of Andisols (Scource: Norman et al, 1984).**



Areas of major occurrence are indicated by circles, and those of minor occurrence by squares.

Table 1: **Generalised distribution of soils in the tropics**

Soil Associations dominated by	Tropical America (m/ha)	Tropical Africa (m/ha)	Tropical Asia (m/ha)	Tropical Australia (m/ha)	Total (m/ha)	Proportion of tropics (%)
Oxisols	502	550	15	-	1067	21
Ultisols	320	135	286	8	749	15
Entisols	124	300	75	93	592	12
Alfisols	183	550	123	55	911	18
Inceptisols	240	156	169	3	532	11
Vertisols	20	46	66	31	163	3
Aridisols	30	704	23	33	790	16
Mollisols	65	-	9	0	74	2
Andisols	31	1	11	0	43	1
Histosols	4	5	27		36	1
Spodosols	10	3	6	1	20	-
TOTAL	1493	2450	810	224	4977	100

Source: Norman *et al.* (1984)

and Southern and Simbu provinces in the highlands. Despite P-fixation being a major constraint, much of the cocoa, oil palm and robusta coffee is produced on these soils and on vitrandepts.

Hydrandepts

Hydrandepts are the dominant highland soils and occur in high rainfall areas between 1500-3000 m.a.s.l. These soils are highly weathered and devoid of silicates.

They are characterised by high organic matter (OM) content with concomitant high C/N ratios (>15) and low bulk densities. Moisture content of these soils rarely falls below field capacity. The pH ranges from 4.5-5.5, but is not associated with the usual Al and Mn toxicity problems encountered by other soil types at these range of pH. Exchangeable bases are low.

Allophane, gibbsite and to a lesser extent halloysite are the dominant clay minerals in hydrandepts (Bleeker 1983). P-fixation is high resulting in widespread P-deficiency. Hydrandepts occur throughout the highland provinces occupying a total of some 25,000 km^2 (Radcliffe 1985) and sustain heavy human and livestock populations and agricultural activity. Harding (1984) listed hydrandepts as a common arabica coffee soil above 1500 m.a.s.l in PNG.

3.0 PROPERTIES OF ANDISOLS

3.1 Clay Mineralogy

Allophane, Imogolite, Gibbsite and Halloysite

The climates of the humid tropics favours rapid weathering. Andisols are developed from the weathering of ash which was deposited from volcanic eruptions many thousands of years ago. The weathering results in the loss of silicon and bases by leaching and in the accumulation of active Al and Fe in the weathered products (Wada 1985). The active Al combines with Si in the absence of OM to form different classes of non-crystalline and crystalline minerals. The dominant and most important are allophane, imogolite, gibbsite and halloysite (Wada 1985; Wada 1981; Parfitt 1978; Tan 1981). In the presence of OM, a strong bonding is formed between Al and humus (Wada 1981; Tan 1981). These materials have distinctive effects on chemical and physical properties of andisols.

Allophane and imogolite are non-crystalline aluminosilicates, which are formed under similar conditions. They are found in lower horizons where OM is deficient or low (Wada 1985). Once allophane is formed it has a high affinity for OM and interacts with it to form organic complexes which resist decomposition and result in the accumulation of organic materials in VAS. Allophane influences the charge characteristics of andisols. In the absence of

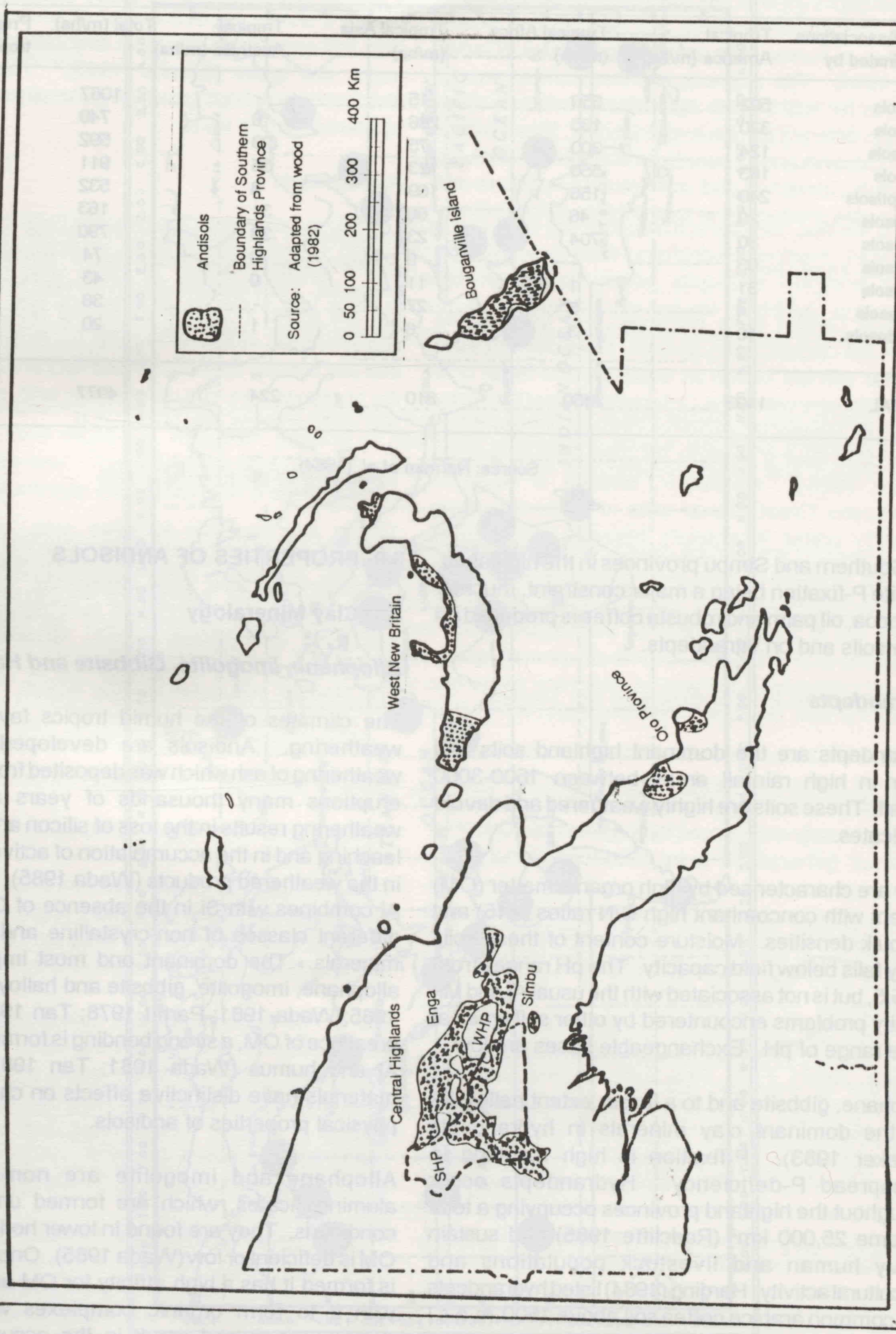


Figure 2. **Distribution of Andisols in Papua New Guinea. (Source: Radecliffe, 1985).**

allophane and imogolite, especially in the high rainfall tropical areas, Al and Fe hydroxides may be abundant (Wada 1985). This may result in an abundance of gibbsite relative to other clay minerals because it is formed of Al and Fe oxides (Tan 1981). Alternatively, the Al may form complex associations with OM, if present. In the warmer lowland tropics halloysite is plentiful because allophane is short lived and is transformed to halloysite (Wada 1985). Such transformation from the allophanic to the halloysitic stage can take upto 15,000 - 30,000 years (Carating 1991).

Little or no halloysite may be present in the high rainfall highland areas. Both gibbsite and halloysite are important clay minerals in highly weathered VAS. An abundance of halloysite usually represents either an advanced stage of weathering or a mixing of non-ash materials (Mitzota & Chapelle 1988). The coexistence of gibbsite and allophane in PNG andisols is documented by Bleeker (1983), Radcliffe & Gillman (1985) and Chartres *et al.* (1985).

In one study the presence of amorphous and poorly crystallised clay materials made mineralogy tracing and its interpretation difficult in some PNG soils (Bleeker 1983). Despite this, other data seem to suggest a distinct altitudinal differentiation in the distribution of allophane, imogolite, gibbsite and halloysite in PNG andisols (Chartres *et al.* 1985; Radcliffe and Gillman 1985). Allophane dominates highland soils (>2000 m), gibbsite between 1200-2000 m and halloysite those below 1200 m. The presence of imogolite, relative to other minerals is not well established. In highland hydrandepts, the order of dominance is allophane > gibbsite > halloysite. This is comparable with a lowland (540 m) typic hydrandept in West Java where weathering resulted in mixed gel > allophane > imogolite > gibbsite in that order of mineralogical dominance (Goenadi 1991). The special properties of VAS are a consequence of the properties of these clay minerals and they determine the soil electric charge and influence the physical and chemical properties of VAS.

3.2 Physical Properties

A good description of the physical properties of volcanic soils rich in allophane is given by Carating (1991) and Leamy *et al.* (1981). Typically, andisols have deep dark to very black top soils. In humid tropical climates the colour may be less dark but more dark brown to dark-red brown. The dark black colour is derived from the ash which is predominantly black. The A horizon is often deep (> 100 cm) and associated with high OM levels (>70%), thus making this profile humus rich, with excellent physical properties. The soil is well structured, friable and easy to work (Radcliffe 1985).

The high OM level in the A horizon is a special and important feature of andisols (McMahon 1987). This has resulted in other distinctive properties such as high C/N ratios (15-20), low BD (0.4 - 0.7g cm^{-3}) and very high CEC (Leamy *et al.* 1981). A particular characteristic is the water holding capacity of andisols, which can be twice that of more common tropical soils, with the water held at considerably lower tensions than most (Sanchez 1976).

Most of PNG highland soils form under freely drained moisture conditions (Radcliffe 1985). Wallace (1971) reported field moisture contents of highland VAS to be in the range 80-190%. He also reported that the effects of drying these soils resulted in an irreversible change in structure and plasticity, implying that the soil is vulnerable to permanent structural damage if a bad drought is experienced.

The B horizon is often brown to yellowish brown in colour. Subsoils are also often friable and permeable, but weakly structured (Radcliffe 1985). The presence of imogolite in andisols is thought to be associated with the puffy, loose, very soft and often extremely friable nature of subsoils, inspite of the high moisture holding capacity of this soil (Leamy *et al.* 1981).

Allophane is naturally stable. Its association with OM results in high aggregate stability, good infiltration in the top soil and high permeability in the subsoil. These properties are said to give andisols resistance to erosion (Leamy *et al.* 1981; Sanchez 1976; Wada 1985). Despite the good structural stability, there is a critical limit beyond which exposure to heavy pressure and compaction, can result in structural deformation and change in strength (Leamy *et al.* 1981). Studies in USA on a VAS heavily compacted by machinery in logging operations have confirmed significant impairment to soil structure and increased bulk density (Geist *et al.* 1989). This implies that the potential for intensive mechanised agriculture on volcanic soils may be limited.

3.2.1 Bulk Density (BD)

Except for young VAS of vitric nature (eg vitrandepts), the usually quoted range of BD (0.4-0.7 g cm^{-3}) for VAS are the lowest of all soils. The high OM content is responsible for high porosity, and the relative lightness of this soil type results in a low BD.

3.2.2 Organic matter

The organic components of soils originate from above and below ground biomass. The breakdown of this biomass is influenced by the quality or nature of the material, soil temperature, moisture, soil acidity, soil microbial population, and in agricultural systems, human and animal activity. In most tropical ecosystems the OM in the soil is rapidly attacked by micro-organisms and depending on N supply, is subject to quick decomposition and mineralisation. Hence, OM is a reservoir for N, P, K, S and other macro and micro nutrients.

In tropical VAS it seems temperature, in particular diurnal fluctuations in soil temperature, moisture and clay mineralogy (Wood 1989) have a more profound effect on soil microbial processes and significantly affect OM breakdown and mineralisation. The literature agrees on some basic facts of OM breakdown. These are (i) OM accumulates to high levels in the cool highland environments of the tropics, and decreases with increased temperature (Wada 1985; Yoo 1984; Goh 1981); (ii) the activity of soil fungi, actinomycetes and other micro-organisims decreases with increased altitude, resulting in an extraordinary build up of immobile OM in the upper profiles of VAS (Tate & Theng 1981; Lozoane *et al.* 1974, cited by D'Souza 1986). OM in this form is complexed with allophane and Al, and becomes resistent to microbial decay (Tate & Theng 1981; Oades *et al.* 1989; Goh 1981), and (iii) low temperatures, low micro faunal densities and high levels of OM in complex associations are suggested to interact in ways which lowers and/or inhibits OM mineralisation and hence nutrient supply to crops.

Soil carbon and N mineralisation rates for soils high in clay and allophane was reported lower than other soils which lacked these materials (Goh 1981; Sanchez 1976; Vander Zaag *et al.* 1984; Oades *et al.* 1989). The actual cause of OM resistance to microbial decomposition remains unknown. It is generally attributed to at least three main causes and represents fertile areas of research (Tate & Theng 1981, Goh 1981):

1. Micro-organism inactivity due to aluminum toxicity.

2. The complex OM - allophane bonding makes OM inaccessible to extracellular enzymes and decay organisms. This may come about either because OM is entrapped within clays, or because clay minerals have a range of effects on microbial processes in soils (Wood 1989; Goh 1981; Vander Zaag *et al.* 1984).

3. Reactive sites on OM are inactivated, probably due to formation of coatings over organic compounds. The formation of complex associations between allophane and OM constituents is a phenomenon common in andisols, and is said to influence soil electric charge.

3.3 Chemical Properties

3.3.1 Charge characteristics & pH

On permanent or constantly charged soils, the electric charge on the soil surface of soil clay particles arises from isomorphous substitution of ions, as occurs when Mg^{2+} replaces Al^{3+}. The soils under review are called variable or pH-dependent charged soils, such as those derived from volcanic ash.

For these soils the charge at which the positive (H^+) ions equal negative (OH^-) ions is called the **Point of Zero Net Charge (PZNC)** (Fig.3). The pH determined here is called the pH at Zero point of charge (pHo). The difference between pHo and field pH (i.e pHo-pH) determines not only the actual net charge of the soil, but also the magnitude of that charge (Radcliffe & Gillman 1985). Hence, at low pH (acidic conditions), andisols exhibit net positive charge and at high pH (alkaline conditions) they exhibit net negative charge (Sanchez 1976). A decrease in soil pH and ionic concentration will result in a corresponding decline in exchangeable bases in andisols. For andisols pHo is often lower than the field pH, resulting in a net negative charge in field situations, but it could be net positive or even a zero charge (Sanchez 1976). Typically andisols are above pH 5.5 (Sanchez 1976).

OM is a variable - charged material (Oades *et al.* 1989) and affects the charge characteristics of VAS. OM content can be negatively correlated with pHo (Fig 4). The agronomic implication of this is that if OM is reduced, as would occur under intensive tillage, the pHo will increase. When this occurs the pHo-pH will result in a positive charge (anionic), and therefore a reduction in ECEC. Similar relationships have been reported for Australian Oxisols (Oades *et al.* 1989).

The dominant factors determining the variable charge nature of andisols, among other influences (see Parfitt 1981; Wada 1985) are:

1. the concentration of cation and anions in the solution, which is determined by the difference between the pH at Zero point of charge (pHo) and field soil pH (ie. pHo-pH);

2. organic matter content; and

3. clay mineralogy, in particular the influence of allophane, imogolite, halloysite and gibbsite (Wada 1981; 1985).

Despite the dominant role of pH, OM and clay mineralogy, some isomophous replacements of ions does occur, especially by small amounts of permanent charge arising from differences in clay mineralogy (Oades *et al.* 1989), or due to lack of OM (Wada 1981), and can interfere with the charge on exchange sites (Sanchez 1976). For example, Radcliffe & Gillman (1985) found that alluvially resorted VAS had a lesser potential variable charge than airfall VAS. In the former there would be less allophane due to weathering, and greater depletion of OM.

3.3.2 Cation exchange capacity (CEC) and base saturation (BS)

The CEC of a soil is an important characteristic related to soil fertility and management. In variable charged soils the CEC, for example of andisols, is often quoted as very high. This is however, an over estimation because the number of cation exchange sites on variable charged soils is determined by the difference between pHo-pH (see Fig 3). As can be seen from Figure 3 the magnitude of negative sites in andisols is small. This has given rise to measurement and interpretation problems, not only of CEC but also for BS (Sanchez 1976). It is very important that agronomists have a correct understanding of these features. Firstly it will facilitate accurate interpretation of soil analytical data, and secondly help identify the appropriate management of nutrients in this soil. Clarifications on this has been provided elsewhere (Kanua 1991).

3.3.3 Anion exchange capacity (AEC)

The important anions in the soils are chlorides, phosphates, silicates, nitrates and sulphates. Relative to cations, relatively few anions, particularly of NO_3 and to an extent Cl, are held by weak electrostatic attraction on clay minerals (Parfitt 1978). Some anions, such as phosphates and sulphates, are strongly held by clay minerals in complex associations, for which reviews on the mechanism of adsorption involved are given elsewhere (Parfitt 1978).

VAS anion fixation, particularly of phosphates, is an important consideration. For phosphates and to an extent nitrogen, a mere statement of their available quantity is an insufficient assessment of the total P & N status. In VAS, P-fixation is very high and nitrogen mineralisation is very low due to high C/N ratio. Therefore determination of the available P and total N must be accompanied by their measurements of anion fixation capacity (Bellamy 1986). These are routinely carried out by commercial laboratories. Generally determination of AEC is less important than ECEC for andisols because, in the field, these soils exhibit negative charge.

4.0 SUPPLY OF NUTRIENTS IN VOLCANIC SOILS

Nitrogen: The organic fraction of the soil phase is the main source of N, P and S. Nitrogen level in VAS', particularly hydrandepts, is often higher than in vitrandepts. Radcliffe (1985) and Wood (1984) reported high levels of total N in highland VAS. In most VAS C/N ratio is high with significant amounts of organic carbon (>1%) and N in the B-horizon which is considered typical of andisols (Sanchez 1976; Bleeker 1983). This results from organic complexes formed from the binding of OM with allophane. However, plants take up N in the form of nitrates. Nitrate - N is also the ion most readily leached from the soil but may not be entirely lost from the system. In a dystrandept significant amounts of Nitrate-N were found in lower profiles (Matson *et al.* 1987) and may be recouped by deep rooting crops.

Phosphorous: Total P-level may be very high but because over 90% of this is locked in the allophane, little is present in the form available to plants, making this nutrient the most limiting for crop production. High P-fixation is one of the diagnostic features of andisols. Al-humus complexes and allophane are considered to be the major materials contributing to the phosphate absorption in andisols (Wada 1985).

The important sources of P are the weathering parent material and the organic fraction of soils. The former depends on the rate of weathering and climatic factors, while the latter depends on biological mineralisation. There is some evidence that organic P is less readily fixed in VAS dominated by halloysite (Bleeker 1983). The management of this nutrient is an important consideration in this study and elsewhere (Kanua 1991).

Potassium: Total K level and the labile pool K in VAS depend, among other factors on the degree of weathering (Graham & Fox 1971 in Sanchez 1973) and organic matter mineralisation, and is closely related to the dominant clay minerals (Hombunaka, 1989). Potassium levels are generally high and better supplied in young VAS (eg. vitrandepts) than hydrandepts . Moss and Coulter (1964) reported considerable amounts of K fixed by the allophane on West Indian volcanic soils but Hombunaka (1989) showed that K-fixation values differ according to methods of measurement, hence, experimental values obtained cannot be compared between methods or between soils.

The critical level of exchangeable K was cited as 0.10 meq per 100g soil for tropical agriculture (Boyer 1972 quoted by Radcliffe 1985). The top horizon of VAS in the PNG highlands are slightly higher but subsoil values are consistently below this critical value (Radcliffe 1985). Of the major elements, K is the most easily leached in VAS, but in other soils, particularly those dominant in 1:1 clay minerals it is the most tightly held nutrient (Mengel & Kirkby 1987).

K-availability to plants depends on its relation to other cations, in particular Ca and Mg. Limited evidence from a PNG VAS (Preston 1990) suggests that the interaction of K with other cations and OM may make this element more available to plants. On the other hand cationic imbalance arising from high Ca/K or Mg/K ratios in the exchange complex, the latter being more common in highland VAS and the former possibly common on calcarious soils, can result in K being made unavailable to plants. This has been reported for a Guatemalan volcanic soil (Tergas & Popenoe 1971) and for PNG by Wood (1984).

4.1 Other Nutrients

The micronutrient status of andisols is not well documented. The excellent review of workers in Central America (Sanchez 1973) is acknowledged and cited extensively here.

Magnesium: Magnesium levels were reported to be low in hydrandepts (Radcliffe 1985), especially in the B-horizon. Low levels of this element with other cations, in particular Ca, often lead to lowering the ECEC of the soil.

Calcium: Ca^{2+} together with Mg^{2+} and K^{+} are the nutrients most readily leached, the rate of leaching increases with annual rainfall and consequently lower the ECEC of the soil (Sanchez 1976). In andisols Ca is leached (Mahilum *et al.* 1970) in the more water soluble carbonic acid which is formed in the presence of CO_2, a by-product of OM decomposition (Mengle & Kirkby 1987).

Sulphur: Most of the S in tropical soils is derived from the OM, whereas in the industrialized world, it is derived from industrial waste and rain water. Like phosphates, a VAS high in allophane and OM will have a high total S-level (Sanchez 1976) because the SO_4 is derived from the organic fraction. The mineralisation of S is however slow, probably because OM is intimately associated with allophane or due to resistance to OM mineralisation by the biological microflora. Mineralised SO_4 is fixed by the allophane anyway, and some are leached making this element available for plant uptake at very low levels in VAS. However, reported levels of SO_4-S from Rwanda (Vander Zaag *et al.* 1984) and PNG (Radcliffe 1985) andisols are adequate. The relative strength at which S is adsorbed and held by the clay is less than phosphate (Sanchez 1976).

Boron: Boron is confirmed deficient in VAS of Hawaii (Fox 1988) Mexico (Sanchez 1976), Chile (Schalscha *et al.* 1973) and PNG (Radcliffe 1985; Bourke 1980). Allophane has a high affinity for boron, making this element together with phosphates and sulphates well retained in VAS.

Zinc: Bajwa (1984) reported widespread Zn deficiency in soils derived from volcanic ash in the Philippines. Radcliffe (1985) reported possible deficiency of Zn in highland VAS. Critical limits of Zn is around 0.4 - 0.6 ppm, and coffee is reported (Bleeker 1983) to suffer from suboptional levels in PNG. Cox (in Sanchez 1973) cited Zn deficiencies in a Costa Rican VAS. Zn deficiency on citrus grown on vitrandepts in New Britain has been confirmed (Bourke 1983).

Aluminum: High levels of exchangeable Al are associated with soil acidity and become a special problem for management of agriculture on many tropical soils. The recorded pH of many VAS are in the acidic range (4.5-5.5), but this is seldom associated with a level of exchangeable Al likely to induce toxicity problems. For example, Radcliffe (1985) and Wood (1984) reported exchangeable Al levels to be only moderate, and not sufficient to induce toxicity problems. However, in a peat soil with volcanic ash influence, Al toxicity significantly reduced yield of maize (Macfarlene & Quin 1989). In another volcanic soil Hombunaka (1989) reported high Al saturation of the ECEC but this did not affect growth of coffee.

Manganese: Radcliffe (1985) reported Mn levels in hydrandepts to be lower than the quoted critical limits of 2-3 ppm. He noted this may indicate possible deficiency of this element. Mn deficiency symptom on plants may be confused for Fe (e.g. Bleeker 1983). Tea grown in organic peat soils have been reported to suffer from Mn deficiency (Bleeker 1983), but has not been confirmed for tea grown in a VAS in the Southern highlands. A limed Columbian VAS was reported to decrease the uptake of Mn by Coffee (Cox in Sanchez 1973). Citrus and robusta coffee grown on a young volcanic soil in New Britain showed Mn deficiency symptoms (Bourke 1983).

Molybdenum: The status of molybdenum in VAS is not clear, but Cox (in Sanzhez 1973) reported that it may be low. Hawaiian and Columbian VAS were reported (Cox in Sanchez 1973) to be low in Mo and suggests this could affect crop production. Cauliflower grown on a VAS at Tambul (PNG) produced the characteristic 'whip tail' Mo deficiency symptom (Mueller, unpubl). In general VAS with low pH (eg. dystrandepts) are likely to suffer from Mo deficiencies.

Copper: Cu deficiency is reported in some andisols (eg, Wada 1985) and is ascribed to stable Cu-OM complex association, as well as inherent low status of this element. Bourke (1983) reported significant sorghum yield response to applied Cu on vitrandepts in New Britain but cautioned that there was limited response to this nutrient in further trials. Tea grown in a highland VAS was confirmed deficient of Cu from foliar analysis (Bourke 1983).

Iron: Levels of Fe in VAS is reported to be adequate (Cox in Sanchez 1973). Fe deficiencies of crops were reported for PNG in soils other than VAS (Bourke 1983).

5.0 NUTRIENT LOSSES IN VOLCANIC SOILS

Plant nutrients are lost from the soil nutrient base in various ways. Nutrient removal by the crop is one contributor. The others being through leaching, run-off and soil erosion.

5.1 Erosion

PNG andisols are ranked very low on a soil erodibility risk class (Bellamy 1986; Bleeker 1983). The detailed study of soil erosion by Humphreys (1984) in PNG was conducted on soils other than volcanic ash. His conclusions were that, even though current rates of soil erosion on bare plots were not excessive, other forms of soil loss, viz; mass movement, rilling, gulling and soil creep, could be substantial. In Tari, on a steep (22-25% slope) garden VAS, Wood (1985) reported that losses were moderate and approached the rate of soil formation (10-15 t ha^{-1} yr^{-1}). These data were not related to crop yield lose.

Soil lost by erosion on a cultivated Japanese VAS was found to range from 9.5 to 15.5m^3 ha^{-1} yr^{-1}, but on pasture established sites was 3.0 to 7.4m^3 ha^{-1} yr^{-1} (Wada 1985). Sanchez (1976) cites evidence of little or insignificant surface erosion and run-off from Guatemalan and Colombian VAS. He attributed this to high permeability of these soils. El-Swaify (1977) using rainfall simulation experiments, evaluated the relative susceptibility of five Hawaiian soils. A entic eutrandept was the most susceptible to erosion but the range of variation was very high even within the andisol group. Another subgroup, typic hydrandept was rated least susceptible and an hydric dystrandept with a typic eutrandept moderately susceptible.

In general, soil erosion on VAS is insignificant and negligible. Most erosion research do not relate soil lose to crop yield lose, probably because the relationship between erosion and productivity is not direct. Despite this, the data provided by Wood (1985) suggests that intensive cultivation of VAS on steep slopes could result in fertility decline through erosion of topsoil. In a poorly fertilized VAS, even small nutrient losses in erosion could have serious implications for crop production.

5.2 Leaching and Run-off

Substantial amounts of NO_3, Ca, K and Mg were shown to be lost to leaching in high rainfall Columbian andisols (Sanchez 1976). Phosphate losses were negligible, probably because it is strongly held by the allophane - OM complexes. No data on micronutrient losses to leaching were provided. Kano (cited by Wood 1984) analysing nutrient contents of rivers flowing through volcanic regions found high levels of bases which he attributed to intensive leaching of bases from the ash deposits. Losses of topsoil by erosion, and nutrients by run-off and leaching, was concluded by Wood (1984) to aggravate soil fertility decline on VAS cultivated on steep slopes in the highlands of PNG. The overall effect of leaching, especially of bases, is the lowering of the ECEC and decrease in pH.

B. CULTIVATION AND MANAGEMENT OF VOLCANIC SOILS

6.0 CULTIVATION OF VOLCANIC SOILS

6.1 Changes in Soil Physical Properties with Cultivation

The deterioration of soil physical properties with cultivation is recorded for many soils of the tropics. Evidence from cultivated Japanese VAS shows that with cultivation, OM content falls and structural systems deteriorate. This is more marked in the warmer southern regions (Wada 1985). Cultivation on PNG VAS was reported to cause little change in soil physical properties (Wood 1985). Wood (1985) reported higher infiltration rates, lower B.D, higher porosity and a greater proportion of water stable aggregates than would normally be experienced with other soils. Radcliffe (1985) noted that the combination of high aggregate stability and infiltration in the topsoil, and permeability in the subsoil gave these soils resistance to erosion and stability to soil structure.

The evidence from Japan contradicts that reported for PNG. A possible explanation is that the regular use of composed material in PNG VAS helps to maintain soil structure and avoids the depletion of soil physical fertility (Kanua 1991). Productivity on VAS measured by sweet potato as test crop throughout the highlands (Goodbody 1983; Floyd *et al.* 1988; Preston 1990) appears to be comparable with yields obtained elsewhere (e.g. Tusno 1970) but not conclusively so. This is despite the greater intensity of land use on VAS than on non-ash derived soils, probably because of their good and stable physical properties. For the moment, soil physical properties do not appear to impose constraints to crop production on PNG VAS.

6.2 Changes in Soil Chemical Properties with Cultivation

The principle constraints to agricultural production on VAS are likely to be imposed by chemical properties. The specific chemical properties of weathered andisols that are likely to limit production on VAS are:

- low availability of phosphates and high P-fixation,
- deficiencies of B, Zn, Mn, Mo and possibly other nutrients,
- low ECEC; and
- low base status and therefore low pH.

Under low pH (acidic) conditions micronutrients such as Zn, Cu and Mn can be in excess. In such situation high levels of Zn for instance, can suppress uptake of P and Fe (Mengle & Kirkby 1987). In general, despite such behavior of micronutrients, their uptake rate is pH dependent and seems to be highest in the mild acidic to neutral pH range (Mengle and Kirkby 1987 see also section 4.1).

Bleeker (1983) showed that so long as crop production on VAS is maintained by continuous fresh compost application, soil chemical fertility (% organic Carbon, % Nitrogen and CEC), with the exception of soil pH, is not drastically reduced on hydrandepts compared to a non VAS (humitropept). Radcliffe (1985) concluded that these problems would become more apparent with intensity of cropping. Wood (1979; 1984; 1985) presented similar conclusions on VAS in Tari and Karamui.

In Tari, Wood (1985) reported exponential decline of exchangeable K with cultivation time. It is noteworthy that K, the nutrient most heavily demanded by crops like sweet potato and coffee, declines sharply over the first five years of cultivation and continues to do so as garden age increases more in the VAS than the non-ash soils. He also obtained highly significant negative correlations between exchangeable Mg, Ca, CEC, % BS and total N on garden age on the soils derived from volcanic ash. The decline in soil chemical fertility with garden age was also associated with a decline in sweet potato yield. This decline in VAS was markedly lower than for other soils. Similar results were obtained on a vitrandept, yield of sweet potato tubers declined from 20-28 t ha^{-1} in the first cropping year to less than 5 t ha^{-1} after 33 years

(Bourke 1977).

The data reported by Wood (1984) for another VAS showed a decline in exchangeable Ca, Mg, total exchangeable bases, % BS and soil pH with cropping time. He noted that there was a gradual increase in soil nutrient content with long fallows on these soils, but that the rate of nutrient recovery was slower than the decline which occurred with cultivation. Similar data from Korean VAS showed that extractable Al decreased in the topsoil but increased markedly in the subsoil with length of cultivation in citrus orchards (Yoo 1984). Yoo also showed that % OM was weakly correlated with extractable Al in the topsoil but the variables were strongly correlated in the subsoil with more than 30 years cultivation.

6.3 Crop Responses to Fertilizer Application

The easiest but not necessarily the cheapest way to solve soil fertility problem is by the addition of inorganic fertilizer. The alternatives are to use organic manure or to practice shifting agriculture. The choice becomes limited under increased land pressure. Under such situations increased crop yields per unit of land area will depend on increased resource investment. To optimise returns from organic and inorganic fertilizer investment, crop responses to these amendments in andisols must be known.

It is highly likely that amendments of nutrients identified at suboptimal or deficient levels in VAS, will give crop yield responses. However, the response of an applied nutrient depends on the soil clay mineralogy and the relative crop requirement for the nutrient and to some extent soil temperature (Fox 1979). These factors become important in fertilizer recommendations so that major economies in fertilizer use are made. These aspects are now considered.

6.3.1 Inorganic fertilizer response

Most studies have shown that because of the high P-fixation capacity and slow mineralisation of OM, VAS are responsive to the addition of major nutrients (N,P,K). The relative magnitude of the effect of N, P & K, as well as Ca, Mg and S, and other nutrients does, however, vary among ash derived soil types.

Nitrogen response: The effect of N in Chilean volcanic soils (Trumaos) on the yield of wheat and beet (Almeyda 1969), and PNG highland VAS on the yield for sweet potato (D'Souza & Bourke 1986a) were limited. The inherently high N-levels in these soils is the reason for this lack of response. However, VAS low in OM are likely to respond to N-application, as reported for a vitrandept (Bourke 1977) and for a young volcanic soil in East Java (Soedarjo *et al.* 1988). Nitrogen tends to promote vegetative growth of crops like beet and sweet potato. In high rainfall areas, anionic (nitrate) or urea, rather than cationic (ammonia) N-fertilizer is recommended (Arana 1969). This is because the NH^+_4 ion has a strong ability to displace Ca, Mg & K in the soil, which are then lost to leaching.

On a highly fertile andic dystropept, applications of 200 kg ha^{-1} yr^{-1} of each of N (ammonium sulphate) and K (K_2O) did not, at first give any significant coffee (green bean) yield responses (Harding 1993). However in the final year of this five year fertilizer experiment there were indications of significant yield responses.

Phosphorus response: Using survey data of sweet potato gardens on hydrandepts in PNG, Goodbody & Humphreys (1986) obtained highly significant positive linear correlations for first harvest yields on soil pH, available P and P retention. Higher yields resulting from increasing P retention is unlikely. However, raising soil pH and increasing available P can both be achieved from a heavy application of phosphatic fertilizers. This finding suggests that P application on andisols, particularly hydrandepts, is likely to give a response.

Crop response to applied P is fairly well established because of the low level of available P in VAS. Almeyda (1969) reported wheat, beet, rape and potato responses to P on Trumaos soils. Almeyda also reported residual effects of P applied two years earlier on beet and clover yield on this soil. However, the residual response was in part attributed to localised placement of P rather than broadcasting, the effect was greatest for beet. Appropriate methods of fertilizer P application are required especially in high rainfall areas because availability of P in the soils fluctuates over the season according to the rainfall pattern (Arana 1969).

Floyd *et al.* (1988) found significant sweet potato responses to fertilizer P and K application on PNG highland VAS. The response of P relative to K, was greatest on these soils, and proved inconsistent with the belief that sweet potato has a low P requirement (Fox 1979). However, Floyd *et al.* (1988) found that the crop response to applied P was reduced by increased mycorrhiza activity. D'Souza and Bourke (1986a) obtained only a small response from P relative to K in Nembi Plateau, and attributed this to low levels of K on the studied soils.

Manuelpillai *et al.* (1981) reported an increasing response to P on three successive soybean crops in a West Javan hydric dysterandept, the response was greatest on the third crop. In East Java Soedarjo *et al.* (1988) reported significant maize yield responses to P_2O_5 on a young VAS.

Potassium response: Beet did not respond to K on Trumaos soils whereas potatoes did (Almeyda 1969). Maize did not respond to K on a young VAS in East Java (Soedarjo *et al.* 1988). Application of K_2SO_4 had little effect on wheat, but where there was a response, it was mainly attributed to S and only to a lesser extent K (Almeyda 1969). Coffee grown in VAS must be adequately supplied with K for which this crop has a high demand (Hombunaka 1989). Manuelpillai *et al.* (1981) reported good response to lime and K by soybean grown on dystrandeps in West Java.

Tusno and Fujise (cited by Tusno 1970) noticed that in Japanese VAS, exchangeable K was high in the subsoil, and this, coupled with deep rooting tuberous roots, was responsible for giving high average sweet potato yields. In field experiments with deep K placement, they found that K alone was not effective but that the combined effect of K and N gave better sweet potato yields. They observed that N and K together were required to keep roots healthy for a longer period of time, rather than K alone.

Maximum tuber yields of sweet potato are achieved at a lower fertilizer N:K ratio (i.e, <1:3) (Norman *et al.* 1984), but this is modified with intensity of land use. A higher ratio of K:N is likely to give yield response on intensively used sites, as reported for an Oxisol in Sierra Leone (Geoffrey-Sam-Aggrey 1976).

Other nutrients: The critical limit for B is around 0.3-0.5 ppm. Hydrandepts of PNG were quoted to be lower than this value (Radcliffe 1985), indicating that crop response to this nutrient is likely. This was confirmed by D'Souza & Bourke (1986) with responses by *Casuarina oligodon* to B-application. Boron applied to sweet potato suppressed tuber yield. Vine yield was significantly increased by the application of B, Mg, Zn, Mn, Co and S on a VAS, but except for B, foliar analysis did not confirm an increased uptake of these nutrients (D'Souza & Bourke 1986a).

As in the case of P (Arana 1969) seasonal flushes of SO_4 in VAS have been reported (Radcliffe 1985) and this is probably due to alternating wet and dry seasons in this region. This means that seasonal crop responses to native S are likely. A maize yield response to sulphur was recorded on a young volcanic soil in East Java (Soedarjo *et al.* 1988).

Al and Mn toxicity can be a common problem on acid soils but is not generally reported for VAS. Rather, suboptimal levels of these elements are reported for VAS. In only one case in PNG, it was reported (Macfarlene & Quin 1989) that Al toxicity reduced maize yields significantly on a peat soil highly influenced by volcanic ash. In contrast citrus and robusta coffee grown on a young VAS in New Britain showed Mn deficiency symptoms (Bourke 1983). In citrus, combined Mn and Zn foliar spray removed Mn deficiency symptoms, indicating a positive Mn * Zn interaction because Mn application in the absence of Zn, did not completely remove the symptom.

For most of the heavy metal cations (Cd, Co, Zn, Cu and Pb), andisols containing high amounts of allophane and imogolite will have a high adsorption capacity for these (Wada 1985). Therefore crop responses to these nutrients are highly likely. However, information on crop species requirements of these elements is scanty.

6.3.2 Organic fertilizer responses

In Japanese VAS compost application was reported to significantly increase sweet potato yield, and improve soil aeration and maintain favourable soil moisture levels during tuber bulking time (Tusno 1970). Floyd *et al.* (1988) found linear responses to sweet potato yield with increasing compost rates on seven ash derived soils in PNG. The maximum yield attained was about 17 t ha^{-1} with 100 t ha^{-1} of *Ischaemum polystachyum* grass. The practical constraint in exploiting the linear yield response is the problem of gathering large quantities for fresh material. Elsewhere in this area D'Souza and Bourke (1986b) recorded quadratic response curves of tuber yield on compost rates for three different composting materials.

Some of the commonly used organic manures in the study area are mixed grass, sweet potato vines and coffee pulp. In experiments, pig manure, *Azolla* fern, *Ischaemum* grass and coffee pulp have been used (D'Souza and Bourke 1986b; Floyd *et al.* 1988). The quantity and quality of nutrients supplied by these materials differ between species (Table 2). Chemical

Table 2: **Nutrient supply by some commonly available composting materials in the highlands of PNG**

Compost material	Application rates (t/ha) (Fresh weight)	Nutrient levels kg/ha N	P	K	Reference
Ischaemum grass	10	38	5	36	D'Souza & Bourke (1986 b)
	20	75	10	73	D'Souza & Bourke (1986 b)
	30	113	14	109	D'Souza & Bourke (1986 b)
	40	151	19	145	D'Souza & Bourke (1986 b)
	100(a)	251	33.5	251	Floyd *et al*.,(1988)
Azolla pinnata	30	40	5	30	D'Souza & Bourke (1986 b)
Pig manure	20	113	64	79	D'Souza & Bourke (1986 b)
Coffee pulp	30	73	5	139	D'Souza & Bourke (1986 b)

(a).Floyd *et al.* (1988) also reported values for S, Ca, Mg, Na, Fe, Mn, Zn, Cu and B; these were 44.6, 114.6, 75.3, 1.95, 4.2, 5.2, 1.3, 0.2 and 0.2 Kg ha^{-1} respectively.

analysis data for *Ischaemum* grass shows fairly high levels of major nutrients and gives a reasonable balance of other macro and micro nutrients. Regression equations relating quantity of *Ischaemum* grass (X) and supply of major nutrients calculated from the data in Table 2 are:

Nitrogen = 33.15 + 2.33X (r=0.97)
Phosphorus = 3.82 + 0.312X (r=0.98)
Potassium = 29.7 + 2.347X (r=0.98)

Average nutritive contents of the other manures are also given. Pig manure is a good source of N and P but low in K, while coffee pulp is a rich source of K, moderately high in N and low in P. Traditionally organic materials are applied mixed (Kanua & Rangai 1988), a practice which serves to maintain the balance of nutrient supply to plants. Quantities of applied manure can vary from 10 to 40 t ha^{-1} fresh weight. A economic rate of application was set at 20 t ha^{-1} (D'Souza and Bourke 1986 b).

6.3.3 Residual response of organic & inorganic fertilizer

Floyd *et al.* (1988) found no beneficial residual effect of compost on sweet potato yield. Residual compost manuring effects may be augmented or enhanced by a nominal inorganic fertilizer application. Since OM has a wide C/N ratio in highland VAS (e.g hydrandepts), the prospects for lowering this by fertilizer nitrogen application needs to be investigated.

Data on residual effects on crop yield from inorganic manuring are very limited. Fertilizer P application is said to have good residual effects. However, this appears to be a function of the application method. An initial heavy P - application is reported to give satisfactory residual effects over a number of crops.

6.3.4 The role of Vascular Abascula Mycorrhiza (VAM)

The role of mycorrhiza in the nutrition of cassava, yam and Irish potato roots has been frequently reported (Norman *et al.* 1984). Such associations are important particularly for P uptake, and to a lesser extent for K and S.

Floyd *et al.* (1988) reported that a parameter 'Relative Phosphate (total tuber) yield' of sweet potato (i.e yield at zero fertilizer/maximum or estimated yield * 100) was better related to the soil phosphate requirement (SPR) when the inter-site differences in VAM infection were first accounted for. By multiple regression equations they showed that sweet potato response to applied P is reduced by increased VAM infection. Hence, one of the important factors determining potential site yield (i.e control plots) in these soils is the degree of VAM activity which was related by the multiple regression equation:

Site Yield = 9.1 + 0.96 VAM (%) 3 * 10^{-9} SPR^3(ug -g soil).

Thus the equation shows a higher site control yield (i.e zero fertilizer treatment) was associated with higher VAM infection than expected from site phosphate requirement. These studies indicate that there are important compost * fertilizer P * VAM interactions in the soils and warrant further research.

6.3.5 Nutrient interactions

Preston (1990) investigating compost (C) * fertilizer interaction on sweet potato tuber yields in PNG highland VAS, recorded significant C * K effect on one site. C * N interaction significantly increased vine yield. Unpublished data from elsewhere in this region (Chatteris 1987 - reported by Preston 1988) showed no C * fertilizer interactions. Significant positive C * P effect on the growth and yield of beans and maize, and to a limited extent for cabbages on VAS in the Southern highlands was reported by Floyd *et al.* (1987). Despite the significant interaction effects, the magnitude of response was attributed primarily to fertilizer P application. On a andic dystropept, Harding (1993) reported significant N * K effect on coffee (green bean) yield and showed that high top soil exchangeable K levels were maintained at a lower fertilizer N:K ratio. On a Japanese VAS, sweet potato yield on zero N plus compost treatment plots was comparable with that of ammonium sulphate treated plots. Better yields were obtained when compost and ammonium sulphate were combined.

The fertilizer study of Floyd *et al.* (1988) found no interaction between P * K on the yield of sweet potato. The rates of fertilizer - P used were 0, 250, 500 and 1000 kg ha^{-1} as triple super phosphate. This is equivalent to 0, 52.5, 105, 210 kg P ha^{-1}. Goodbody (1983) obtained highly significant sweet potato yields on similar soils high in OM (7.5%) with an application of 50 Kg P_2O_5 ha^{-1}. In a trial on a VAS elsewhere in this region, Kanua (1990) found significant P * K (and non significant N * K or N * P) effect on sweet potato yield. In the latter study, the rates of phosphate were 0, 25, 50 and 100 kg ha^{-1}. In the light of the major role of mychorriza in the phosphate nutrition of sweet potato in VAS (Floyd *et al.* 1988), it seems likely that lower rates of P application may give a response by positively interacting with the VAM populations. At higher rates of applied P, VAM activity seems suppressed to the extent that even the uptake of K appears affected, resulting in limiting any beneficial interaction effects.

6.3.6 Liming volcanic soils

Liming is usually not a management option but a necessity in correcting soil acidity. Its application results in an increase in the soil pH, with a concomitant decrease in extractable Al levels. Increase in soil Ca and Mg is a secondary benefit and depends largely on the liming material used. The increase in pH will make native anions and cations available to crops. But increase above pH 5.6 is not beneficial in most situations as it results in precipitation of anions and renders them unavailable to plants (Sanchez 1976).

The data from a liming study conducted on a peat soil with volcanic ash influence by Macfarlane & Quin (1989) in PNG showed that liming up to 18 t ha^{-1} on this peat-ash mixed soil (pH 4.8) did not increase the yield of the first maize crop as did phosphate broadcasted at 2060 kg P ha^{-1} (i.e. at zero lime). Application of 2060 kg ha^{-1} alone, as well as satisfying fixation capacity of the soil and increasing the soil P concentration, also increased the soil pH. Such high P-rates are not, however, economically feasible for small farmers. Despite this, a residual maize crop yielded comparably with the first crop on the 2060 kg P ha^{-1} plot. This means that the effect of a initial heavy application of P can be spread over a number of succeeding crops. Broadcast and placement of P in the second planting on this site produced results that were not conclusive. In general, yields were not significantly different between the two methods of P-application (Macfarlene & Quin 1989). Despite this maize yields obtained at a lower level of lime (6 t ha^{-1}) with banded 1000 kg P ha^{-1} was found comparable with yields obtained at 2060 kg P ha^{-1} broadcast.

In a 7.5 years study on the residual effect of liming andisols, Mahilum *et al.* (1970) found that silicon based liming material ($CaSiCO_3$) had a superior effect in reducing exchangeable Al. In this study Ca^{2+} was readily leached away, only negligible amounts were recovered at 1.2 m depth after seven years. This rapid leaching of Ca^{2+} was reported to be responsible for a subsequent decrease in pH. Similar results were obtained by heavily liming another VAS (Rixon & Sherman 1962). In the latter study a significant increase in CEC was contributed by P-application but liming had no effect. On a volcanic ash influenced andic dystropept, Harding (1993) reported that ammonium sulphate fertilizer applications significantly lowered the soil pH. This N - induced acidification was responsible for increasing the leaching of K, Mg and Ca. Liming a Brazillian volcanic soil increased the buffering capacity of the soil but also induced a decrease in the intensity factor, the latter if left unchecked could lead to K-deficiency (Hombunaka 1989).

7.0 MANAGEMENT OF WEATHERED (ANDIC) ANDISOLS

The data reviewed indicate that inherent soil chemical properties of andisols will impose constraints to foodcrop production. In particular the evidence is overwhelming that due to low ECEC in highland VAS, there is limited capacity to retain cations at the field soil pH. It follows that future management of this soil lies in finding ways of raising ECEC. It has been suggested (Radcliffe 1985), that this can be achieved either by raising the soil pH or by decreasing the pHo. The practical ways of achieving this in the field require investigation.

7.1 Raising Soil pH by Liming

In the absence of other data it seems that liming hydrandepts and other more weathered andisols high in allophane is unlikely to give the desired results. However, liming eutrandepts and dystrandepts which are acidic lowland andisols may give a positive response. No data are available at present to suggest otherwise and should be tested in the field.

One reason why liming may not be the preferred management option is that the low K-level is likely to be worsened by an imbalance created by an influx of Ca or Mg, giving high Ca:K or Mg: K ratio. Also raising pH above 5.6 can result in precipitation of anions and worsen the P and S problems of some highland soils (Sanchez 1976). Fox (1981) notes that greater precision is required in controlling pH of variable charged soils than of permanent charged soils.

Despite this the limited data of Macfarlane & Quin (1989) suggests that possible beneficial effects of lime and economic rates of P may be achieved at application rates lower than those used in their study. Moderate quantities of lime are required to raise pH of variable charged soils to about 5.0 in order to reduce Al toxicities (Fox 1981). Exploiting beneficial interaction effects between phosphate and lime represents a fertile area of research.

7.2 Lowering the pHo

We are left with the proposition that lowering the pHo is an agronomically practical option. The two ways of achieving these are, 1) addition of OM and 2) addition of anionic fertilizers (Radcliffe 1985).

7.2.1 Lowering the pHo by organic matter management

OM plays a role in lowering the pHo and increases the magnitude of negative charge in variable charged soils. However, OM levels are already high in VAS, and the prospects for additional increases to ECEC resulting from additional OM inputs may be insignificant. Despite this, the weight of evidence reviewed suggests that the management of OM is still the key to crop production in VAS. There is also the scope for exploiting beneficial OM * inorganic fertilizer interactions.

Mechanisms involved in composting response

The small amounts of available information reviewed indicates that the principle mechanisms controlling yield responses to composting is the chemical and clay mineralogical properties of andisols. The direct effects of compost on the supply of nutrients are:

1) its role in reducing P-fixation by forming complex associations with allophane,

2) since OM is negatively correlated with pHo, it lowers the pHo and thereby increases the ECEC of the soil,

3) as a consequence of 2) losses of bases to leaching are reduced,

4) OM supplies a more balanced nutrition (see Table 2) and supplies it slowly in available form over the growth period (Tusno 1970),

5) it seems that the traditional practice of compost mounding in the PNG highlands ensures nutrients supplied by decomposing material are directly taken up by plants, without going through a soil phase (Floyd *et al.* 1988).

Consistent with 4) and 5) above, Floyd *et al.* (1988) found increased efficiency of use of P and K supplied as compost than as inorganic fertilizer. However this increased efficiency was modified by differences in soils, particularly P-fixation and base nutrition in VAS. Moreover, in the same study Floyd *et al.* (1988) found that site control yield of sweet potato increased with increased VAM infection. Thus, in concluding they speculated that important interactions between compost* fertilizer* VAM could be involved. Despite all their data they were not able to separate the nutrient effects from any physical benefits of compost.

7.2.2 Lowering pHo by addition of anionic fertilizers

Inorganic amendments of anionic, rather than cationic fertilizers, such as phosphate and silicates, are thought to be most effective in lowering pHo (Radcliffe 1985; Mahilum *et al.* 1970), and the concomitant increase in ECEC. In particular, the addition of phosphatic fertilizers, as well as satisfying fixation capacity of the soil, will also increase the soil pH and the available P-level. The benefit of silicate fertilizers (e.g Ca - silicate) is that phosphate adsorption is decreased and P-desorption is increased (Fox 1974). This results in an increased concentration of P in the soil solution, as well as supplying moderate amounts of Ca and Mg.

Whether these amendments should be applied in splits or in concentrated bands, or in a large initial 'blanket' application is not clear. The limited evidence from this review is inconsistent and does not agree on a single method, but it seems band or split application may be preferred over broadcasting or 'blanket' application for economic reasons. For vegetable production on VAS in PNG, recommended fertilizer application was applied within the planting holes or in bands (Crittenden & Quin 1987). Precise placement of fertilizer seems the sensible option for small farmers. A blanket application of large quantities of phosphatic fertilizers is considered an economic investment, but this is not likely to be adopted by small farmers. In the split or concentrated band application, the applied P saturates the adsorption sites in the immediate vicinity and makes P available to plants grown within that area. Each method needs testing in field trials before recommending the best technique. The technical and economic feasibility of achieving this also requires investigation.

The data on the economics of inorganic fertilizer use is scanty. In PNG, Floyd *et al.* (1988) demonstrated that P-application resulted in uneconomic yield increases for sweet potato, while K gave economic yields for the majority of the VAS used in their study. Despite the fact that applied P is uneconomic to sustain maximum sweet potato yields, limited evidence suggests that good yields of the first crop and response by subsequent crops to residual P over a number of seasons, may more than compensate for the high cost of a single P application. In other P - deficient soils such as ultisols and oxisols, applications of 20 to 80 kg P ha^{-1} sufficiently fertilized crops in rotation, its residual effect lasted two years and gave high economic returns to P-fertilization.

7.3 Inorganic Fertilizer Management

Experimental evidence of the response of the staple crop sweet potato and a number of other crops to nutrients is given in Table 3. In general the responses are inconsistent, probably due to differences in soil and varietal characteristics. Despite this, responses to P and to an extent K, are well established for highland VAS. N is not limiting, a lack of response, except on a vitrandept, confirms this. The requirement for N may be to facilitate and enhance micro-organism activity in the breakdown of OM. It seems the future management of N lies in exploiting beneficial nutrient interaction effects (see Table 3). If these can be confirmed in future trials, practical implications for agricultural management are good.

The data available on other nutrients show that Mg, Ca, B, Zn, Mo, Mn and to a lesser extent, Fe and Cu are either deficient or are at suboptimal levels in andisols worldwide. Crop responses to these nutrients are highly likely. Data on the response to these nutrients in PNG andisols is scanty, and represents a priority area for research.

7.4 Management of Soil Organisions

Apart from the role of VAM in the P-nutrition of crops, other soil organisms such as fungi, actinomycetes, earthworms, termites and micro-organisms are also important in soil formation. Little is known about their specific roles in forming volcanic soils in the cooler tropical highland areas. The review shows that in VAS the activity of soil fungi and actinomycetes decrease with altitude implying that the activity of other soil organisms is also likely to be low.

Local PNG farmer's believe that by placing compost inside earth mounds the soil temperature is raised sufficiently to activate the meso and micro floral activity. This belief is consistent with scientific evidence reviewed (see 3.2.2) and can lead to rapid OM-breakdown and mineralisation. These aspects represents fertile areas for further research.

Table 3: **Crop response to organic and inorganic fertilizer application on volcanic ash soils**

Nutrient	rate Kg ha^{-1}	Crop	Response	Country	Reference
N	300	Wheat	*	Chile	McMahon (1987)
	100	S.potato	**	PNG (Enga)	Preston (1990)
	-	S.potato	**	PNG (ENBP)	Bourke (1977)
P	400 (P_2O_5)	Wheat	**	Chile	McMahon (1987)
	120 (P_2O_5)	Beet	**	Chile	McMahon (1987)
	100 (P_2O_5)	S.potato	**	PNG (Enga)	Preston (1990)
	2060 (P_2O_5)	Maize	**	PNG (SHP)	Macfarlene & Quin (1989)
	- (P_2O_5)	Maize	**	East Java	Soedarjo *et al.* (1988)
	75	S.potato	*	PNG (Nembi Plateau)	D'Souza & Bourke (1986a)
	500-1000	S.potato	**	PNG (SHP)	Floyd *et al.* (1981)
	-	Soy bean	*	West Java	Manuelpillai *et al.* (1981)
K	75	S.potato	**	PNG (Nembi Plateau)	D'Souza & Bourke (1986a)
	200-360	S.potato	**	PNG (SHP)	Floyd *et al.* (1988)
	-	Soy bean	*	West Java	Manuelpillai *et al.* (1981)
	-	Coffee	*	PNG	Hombunaka (1989)
S	-	Maize	*	East Java	Soedarjo *et al.* (1988)
B	1.5	*C.aligod on*	*	PNG (Nembi Plateau)	D'Souza & Bourke (1986a)
N * P	150 N, 400	Wheat	**	Chile	McMahon (1987)
	P_2O_5 64 N,	Rape	**	Chile	Almeyda (1969)
	100 P_2O_5	Clover	**	Chile	Almeyda (1969)
	120 N, 180 P_2O_5				
N * K	-	S.potato	*	Japan	Tusno (1970)
P * K	50 P, 150K	S.potato	**	PNG (Gumine)	Kanua (1990)
Mn * Zn	-	Citrus	*	PNG (Keravat)	Bourke (1983)
Compost	67 t/ha	S.potato	**	PNG (Enga)	Preston (1990)
(C)	100 t/ha	S.potato	**	PNG (SHP)	Floyd *et al.* (1988)
Pig manure	20 t/ha	S.potato	**	PNG (Nembi Plateau)	D'Souza & Bourke (1986b)
Coffee pulp	30 t/ha	S.potato	**	PNG (Nembi Plateau)	D'Souza & Bourke (1986b)
C * K	6.7 t/ha C 100 K	S.potato	**	PNG (Enga, Tuluma)	Preston (1990)
C * P	-	Maize	*	PNG (SHP)	Floyd *et al.* (1987)
P * Ca (1)	300 P_2O_5 4000 CaO_3	Wheat	-*	Chile	Almeyda (1969)
Lime	2,500 $CaCO_3$	Alfalfa	*	Chile	Almeyda (1969)
	6 - 18 t/ha	Maize	*	PNG	Macfarlane & Quin (1989)
	$CaSiCO_3$	Soy bean	*	West Java	Manuelpillai *et al.* (1981)
Lime * P_2O_5(2)	6 t/ha 1000 P_2O_5	Maize	*	PNG (Kuma, SHP)	Macfarlane & Quin (1989)

* - positive, small response
** - highly significant response
-* - significant negative response
(1)- The P * Ca interaction is negative at high P_2O_5 levels only. P-alone is effective
(2)- Results were not conclusive but a Lime * P positive interaction is highly likely at lower rates of these materials.

8.0 CONCLUSION

Crop production on VAS in the PNG highlands is governed essentially by rainfall and soil type. High rainfall regimes are responsible for the rapid leaching of bases. This results in lowering the pH and ECEC. It was suggested that in cooler highland regions the interaction of high OM levels, coupled with low microfaunal population and low temperatures, results in complex processes which may inhibit both OM mineralisation and nutrient supply to plants. In addition VAS high in allophane retain important anions such as phosphates and sulphates, and micronutrient cations such as B, Mo and Zn, and render them unavailable to plants. All these factors together contribute to giving VAS their peculiar characteristics and make their management difficult.

Against the backdrop of a harsh soil and agroclimatic environment, traditional management seems to have developed practices specifically to curb these problems. The compost-mounding and improved fallow planting (Kanua & Rangai 1988) are examples of these. The information reviewed show that OM plays a vital role in maintaining soil physical and chemical fertility. As well as sustaining soil aggregate stability and other physical benefits, OM supplies a wide range of nutrients, and makes them directly available to crops. Coupled with this it plays the role in increasing the magnitude of the negative charge sites, and hence ECEC.

It must be concluded that the traditional practice of compost-mounding is an important activity, and that the key to the management of highland VAS in PNG lies in the continuous application of organic materials. To improve this qualitatively, requires the supplementation of compost vegetable materials, perhaps through a selective planted and/or simultaneous fallow. Despite the fact that data on inorganic fertilizer response in andisols is somewhat inconsistent, there is scope for exploiting beneficial organic * inorganic fertilizer interaction to augment crop responses to organic manuring.

Crop diversification seems a logical proposition for farmers. Maize would be an ideal candidate (see Floyd 1985), but the low chemical fertility of this soil means that the production of maize or any other introduced crop will have to be supported by heavy fertilizer applications. The alternative is to continue to rely on low nutrient requiring crops such as sweet potato and other tuber crops. The traditional system of crop variety selections has resulted in varieties suited to different soil situations, and are particularly adapted to low levels of nutrient supply. Their yield is not high and substantial improvement in soil nutrient status will require the introduction of new varieties to make full use of the changing conditions. Farmers appear to be satisfied with their current level of production using their present soil and crop management practices. The need for improved crop varieties and for better management practices will become apparent when increased population pressure increases the demand for more food, and therefore more cultivable area.

9.0 ACKNOWLEDGEMENT

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10.0 ACRONYMS

AEC - Anion Exchange Capacity
BD - Bulk Density
BS - Base Saturation
C - Compost
CEC - Cation Exchange capacity
ECEC - Effective cation Exchange Capacity
m.a.s.l - meters above sea level
OM - Organic Matter
pHo - Point of Zero Charge
PNG - Papua New Guinea
PZNC - Point of Zero Net Charge
SPR - Soil Phosphate Requirement
USDA - United States Department of Agriculture
VAM - Vascular Abascula Mycorhiza
VAS - Volcanic Ash Soils
***** - Multiplication (eg. C * K).

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