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Special Issue

SOIL RESEARCH AND MANAGEMENT IN PNG

Edited by: Alfred E. Hartemink
(University of Technology, Lae)

PAPUA NEW GUINEA

JOURNAL OF AGRICULTURE, FORESTRY AND FISHERIES

Special issue: **SOIL RESEARCH AND MANAGEMENT IN PNG**

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Preface

There were about two million people in Papua New Guinea in 1966. Today, there are over four million. Amongst others, such population increase could not have occurred without a higher food production and substantial food imports. The increased food production resulted from better crop husbandry practices (mounding, composting etc.) as well as higher land-use intensities, that is to say, shorter fallow periods. But agricultural research has also played a role in the increased food production. The *Papua New Guinea Journal of Agriculture, Forestry & Fisheries* previously known as the *Papua New Guinea Agricultural Journal*, has for 50 years been the sole national publishing medium for agricultural research in the country. The journal has experienced some vicissitudes but currently appears with one or two issues per year. This is a special issue of the journal dedicated to one of the natural resources on which all food production depends: the soil.

Papua New Guinea has a long and interesting history of soil research of which Dr Geoff Humphreys gives an overview in the first paper of this issue. Mr David Freyne describes in the second paper PNGRIS (Papua New Guinea Resource Information System) which contains digitized information on the natural resources, land use and population of the country. There is a large soil component in PNGRIS that, as the author shows, can be used for several purposes. Mr David Radcliffe and Mr Matthew Kanua used PNGRIS to estimate the cover of Andisols and they review the specific chemical and physical properties and management of these soils in the third paper. Although Andisols cover a relative small area, they are extensively used for cultivation. Coffee is an important source of income for one-third of the population in Papua New Guinea and Dr Paul Harding and Mr Potaisa Hombunaka review the nutritional aspects of the crop. They summarize many years of research conducted at the Coffee Research Institute and throughout other parts of the highlands.

Plantation agriculture earns the country cash but also supplies domestic needs like for example the sugar from Ramu Sugar Ltd. Our work at the sugar cane plantation has indicated significant soil changes since the plantation was established in 1979 which may affect production if such trends were to continue. The paper is followed by three papers on sweet potato production. Sweet potato is the main staple crop in Papua New Guinea and research aiming at yield improvements is likely to have large impact. The first paper by Mr Matthew Kanua indicates that inorganic fertilizers may have significant yield effects. Although inorganic fertilizers are hardly used by smallholders this may have to change in order to increase food production. The other two papers deal with sweet potato production in agroforestry systems. Over 20 years of research in other parts of the world has shown that agroforestry has a large potential of high base status soils on steep slopes and in areas of high rainfall. Such conditions occur in many parts of Papua New Guinea. The last two papers dealing with research conducted in the lowlands of Morobe province, generally confirm the agroforestry potential.

The authors should be wholeheartedly thanked for their contributions to this special issue. Mr Reuben Sengere and Ms Betty Aiga of the DAL publication section are thanked for the lay-out of the papers and preparing them for the printery. Several anonymous referees are acknowledged for their review of the manuscripts. It is hoped these efforts would contribute to a sustainable agricultural development of Papua New Guinea for which a profound understanding of the soil resources and their management is essential.

Alfred E. Hartemink
Lae, June 1998

A REVIEW OF SOME IMPORTANT SOIL STUDIES IN PAPUA NEW GUINEA

G.S. Humphreys*

ABSTRACT

This paper attempts to provide an appreciation of the variety of soil studies that have been undertaken in Papua New Guinea (PNG). The main themes considered and the reasons why they were investigated include: (i) land evaluation, in which considerable contribution has been made in assessing suitability of various cash crops at plantation and smallholder levels; (ii) land system mapping, where the results were built into a robust natural resource database and eventually linked to a GIS that covers the whole country on a scale of 1:0.5 M; (iii) soil erosion studies, where the results indicate low to modest soil loss rates despite high rainfall and high relief over much of the country; (iv) soil conservation, in which it was found that over much of the country the traditional conservation practices are based on the principal of removing water without causing erosion rather than retaining water; (v) soil fertility, especially the problems concerning the interpretation of data and highlighting the variety of approaches used to evaluate nutrient and yield decline and recovery on traditional garden plots; (vi) soils and human health, which though an unusual topic identify issues worthy of further research; and (vii) pedogenesis, in which latosols are used as the main example though references to other soil types. The problem of the difficult terminology especially with regards to soil classification is highlighted.

Key words: *soil erosion. soil conservation, land evaluation, land systems, soil fertility.*

INTRODUCTION

In this review the expression 'soil studies' is chosen deliberately so as to encompass traditional soil science, which is normally associated with agricultural and forestry pursuits, as well as themes within earth and environmental sciences. In this sense the review attempts to be broad ranging but it is somewhat restrictive in the material covered. This selectivity reflects more the authors' interests and experiences in working and conducting research in PNG rather than any profound rationalisation. Accordingly, any criticism that the review covers too many topics too briefly is valid. But the aim of this review is to provide an appreciation of the variety of soil studies already conducted in PNG, especially to new comers whether they are recent graduates or trained in different disciplines. Consequently the paper is organised on a topic basis rather than highlighting the achievements of particular individuals. A secondary aim is to provide a sense of historical background as to why and how particular research themes were selected. However, by its very nature it touches on potentially difficult grounds since most of what is published by researchers is technical and the behind-the-scenes reasons for the study in the first place are not always presented.

SOIL INVESTIGATORS AND THEIR LANGUAGE

Until the last fifteen years or so all published information on soils was provided by expatriates.[i] Of course national staff such as labourers and technicians contributed in various ways to this early expatriate input. The most visible has been the contribution by CSIRO (Australia) through their land systems mapping and policy to publish in international journals. In terms of sheer volume the Land Use officers of DAL have provided the greatest con-

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tribution but the vast majority of this is contained in reports accompanying reconnaissance mapping and much of it remains unpublished in departmental files. The last major source has been provided by university researchers and consultants and whilst the overall volume is not great the variety of subject matter must be acknowledged. It has really only been since Independence that PNG nationals have contributed directly to scientific knowledge of nation's soils. The contribution is dominated by Land Use Officers and other agricultural staff, and to a lesser extent by the university staff.

Papua New Guinea has a rich knowledge of soils especially in terms of fertility (the 'grease' factor in *Tok Pisin*), workability (ease of digging) or some other factor that identifies a special use or an undesirable quality (e.g. Sillitoe 1993 a). This knowledge and detailed language is to be expected given the reliance on root crops and the existence of agricultural systems that are noted for their high crop and cultivar diversity, complexity in cropping practices and in soil amelioration practices.[ii] Unfortunately, this knowledge remains largely untapped. The few published accounts are primarily investigations incidental to other interests and it is apparent to even the most casual inspection that considerable knowledge exists.[iii] For example, the Huli possess an extensive knowledge of how to deal with volcanic ash falls such as marking gardens to help locate harvestable produce and storing drinking water. They are aware also that high crop yields follow such events because of the added 'grease' (i.e. additional supply of soil nutrients) even though the last known ash fall occurred about 300 years ago (Blong 1982). There is considerable merit in attempting to understand why certain practices are pursued such as in the choice of fallow lengths and cropping cycles. The reasons given may be obscure but they deserve further investigation and one of the greatest challenges faced by government bureaucracies such as those in DAL is to incorporate this information into research programs.

Not surprisingly, most information obtained thus far is from the viewpoint of western knowledge. An interesting example of this is an attempt to assess the degree of sophistication of the local language in dealing with soil types. For example, Brookfield and Brown (1963) noted that the Kuman speakers of Simbu have no collective term for a soil profile and appeared to label the material and not the vertical sequence. Ollier *et al.* (1971), Lansberg and Gillieson (1980), and Wood (1984) reiterate this viewpoint from other language groups. In this context the absence of the equivalence of a soil profile was viewed as indicating a less than satisfactory approach i.e. it did not match prevailing scientific thought. It is interesting to note that in some circles in soil science there is a move to replace soil profiles with soil layers as the main unit of soil classification (e.g. Atkinson 1993; Paton *et al.* 1995). Soil layers correspond much more closely to the basic unit of organisation adopted in local languages in Papua New Guinea.

One of the main constraints to the dissemination of information to user groups such as other researchers, government agencies and land managers is closely tied to the language and classification systems adopted for this purpose. For the most part the classification of soils is very obtuse and remains largely unintelligible to others. One of the implications of this is that there are relatively few people who understand soil classifications and this is especially so in developing countries. In 1975 PNG adopted a soil classification system known as Soil Taxonomy (Soil Survey Staff 1975, 1992), a product of the United States Department of Agriculture. At least part of the rational stems from a desire to ensure PNG soil studies would be more accessible to an international audience (see Bleeker 1983) and to facilitate agrotechnology transfer which was a popular issue around this time.[iv] Unfortunately Soil Taxonomy is a complicated and expensive classification system relying on laboratory analyses of chemical, physical and sometimes mineralogical properties in order to fully classify a soil type even though the basic features can often be identified in the field using morphological attributes. Furthermore, this classification scheme is biased to soils commonly found in temperate areas of the northern hemisphere and many of the categories especially those based on moisture and temperature regimes have little meaning in PNG (Haantjens and Bleeker 1975; Humphreys 1991). To help overcome these difficulties a modified version of the forerunner to Soil Taxonomy, the 7th Approximation, was developed and used by CSIRO workers in PNG for several years (see Haantjens and Bleeker 1975). However, this modified version was abandoned in 1975. If it had been more widely used and developed PNG may well have had a more serviceable soil classification scheme. An alternate approach that overcomes the problems in using a hierarchical classification such as Soil Taxonomy is to adopt a nodal based classification i.e. a system that emphasises a core concept rather than concern itself with definitions at the boundaries between one node and another. This type of approach was used in PNG into the 1960's in which an assortment of terms based on great soil groups, mostly from USA and Australia, was employed. Modern developments in fuzzy logic and associated statistics has strengthened the robustness of the nodal approach. However, there are few soil types in PNG that have been sufficiently well studied that most workers would accept as a nodal soil. The one obvious exception is the "humic brown clay", a type of andisol, which is a widespread volcanic ash soil found mostly in the highlands.[v] The main reason for this nodal status is that the characteristics of this soil type are sufficiently distinctive that they are readily understood by various user groups, the extent of which may surprise some researchers.[vi]

Other soil types with distinct morphologies or that appear to be important because they are widespread, and which could be developed as nodal soils include the following: cracking clays (vertisols), clayey colluvial mantles (some tropepts/orthents), texture-contrast soils (various alfisols/ultisols), pumiceous volcanic ash soils (andisol), certain organic rich materials and several others. The cracking clays form a distinctive group but are restricted mostly to valley fills in drier areas. Similarly, texture-contrast soils have a distinct morphology. They are known in Western Province (Bleeker 1983) and Irian Jaya (Schroo 1964). A gravelly texture-contrast variant occurs on lower hillslopes in the Port Morseby area (Scott 1965; Mabbutt and Scott 1966; Paton *et al.* 1995). Pumiceous volcanic ash soils are also distinctive and often have sandy to loamy textures (Bleeker and Parfitt 1974) with mineralogies conforming to a recent origin associated with the present day island arc. However, the relationship between well weathered varieties and the humic brown clay needs further investigation. Dark pedal clays or rendzinas (rendolls) are common on limestones and some very calcareous mudstones. However, in some locations deeper and redder alkaline clayey soils (rhodustalfs, rhodudalfs) occur on limestone. They may indicate a significant contribution of volcanic ash such as on the Pleistocene raised terraces of the Huon Peninsular (Bleeker 1983). In addition some limestone soils contain high levels of phosphorus. These were first reported in Irian Jaya by Schroo (1963) and Bleeker (1983) predicted that similar occurrences should be found in PNG. This was verified by Macfarlane *et al.* (1990) who reported high phosphate levels in some raised limestone reef areas in Milne Bay Province. Clayey, colluvial soils are widespread in PNG but those formed on calcareous marine mudstones such as the Chim Formation are particularly noteworthy since even the saprolite is quite fertile (e.g. Goodbody and Humphreys 1986). Other colluvial materials are poorly understood and a high degree of variability in fertility status renders evaluation at this time difficult. Various latosols (ultisols and oxisols) occur as well and this soil type is used as an example to explore some issue dealing with its identification and origin. Peats and other organic rich sediments (various histosols but also entisols and various aquic suborders) are widespread in PNG and some of these are highly valued for traditional crops and for growing tea. The high production potential of many of these soil variants requires further study to assist in promoting optimal usage.

In addition there are a variety of soil types which possibly occur but are very poorly known. Acid sulphate soils (sulfaquents/sulphaquepts) are expected in mangrove areas especially in estuarine settings (Bleeker 1983) but unless these are drained or otherwise aerated the very low pH condition and other associated properties may not develop. Podzols (spodosols) have not been positively identified in PNG though there is an unconfirmed report of a podzol at Kiunga on the Fly Platform (D. Freyne pers com.). Hardon (1938) reports a podzol in the Arfak Mountains in Irian Jaya but the description indicates a texture-contrast soil rather than the sandy podzols found elsewhere in the tropics such as in Malaysia (Richards 1941).

LAND EVALUATION

A full history of land evaluation in PNG has not been written but it would prove a worthwhile task as implied in several useful reviews (e.g. Bleeker 1983; Dearden *et al.* 1986; Brasher *et al.* 1995). In some respects it has closely followed international developments but it has also pioneered other approaches that would surprise many who are unfamiliar with local literature. Land evaluation involves the systematic assessment of land so as to ascertain the most suitable use of that land. Normally, it is used in the context of agricultural land use but it is also applies to forestry, water catchments, flora and fauna reserves and other purposes such as geomorphic hazard assessment (e.g. Hearn 1995). The basic information used in land evaluation is the soil and hence soil scientists have been very much involved. From the outset effort was placed into soil surveys by DAL's Land Use Section. The first land evaluation scheme used in PNG was developed by Haantjens (1963, updated 1969). His Agricultural Land Classification applied to commercial agriculture of arable crops, tree crops, improved pastures and irrigated rice. The scheme was based on the first widely accepted international land evaluation scheme, the Land Capability Classification (LCC) (Klingbiel and Montgomery 1961) but as the latter was devised for high input American farms it required extensive modification for possible plantation use in PNG. It is thought that Haantjens' scheme represented the first realistic application of LCC ideas to tropical conditions. It was also devised for smaller scale soil mapping and in particular the reconnaissance mapping involved in Land System Surveys which contrasted to the large scale soil mapping base used in LCC. Subsequently Haantjen's scheme was modified and applied across PNG at a map scale of 1:1 M (Bleeker 1975) as part of a series or resource maps produced at the same scale.

The LCC approach focussed on limitations to crop/pasture production in general. During the 1970's a new approach was devised based on the suitability of the land for a specific crop. Land Suitability Evaluation (LSE) as it is best known is the most widely applied outcome of the highly acclaimed Framework for Land Evaluation (FAO 1976). In some ways Haantjens' scheme anticipated aspects of LSE as did the scheme devised by Hartley *et al.* (1967) to rate land suitable for a variety of crops in West New Britain. LSE has been successfully applied in PNG to commercial cocoa (Bleeker and Freyne 1981 and Wayi 1987), plantation and small holder arabica coffee (Harding *et al.* 1986) and sweet potato (Radcliffe 1983). Subsequently, Venema and Daink (1992) extended LSE to encompass a variety of low input crops such as cardamom and higher input crops. Known as PNGLES (PNG Land Evaluation Scheme) it has become the standard means of land evaluation in PNG. In addition an ecophysiological approach for matching plants to land was developed within CSIRO for use in PNG and elsewhere (Hackett 1988). This approach represents a considerable advance in suitability assessment but depends on detailed information on the environment to be truly useful.

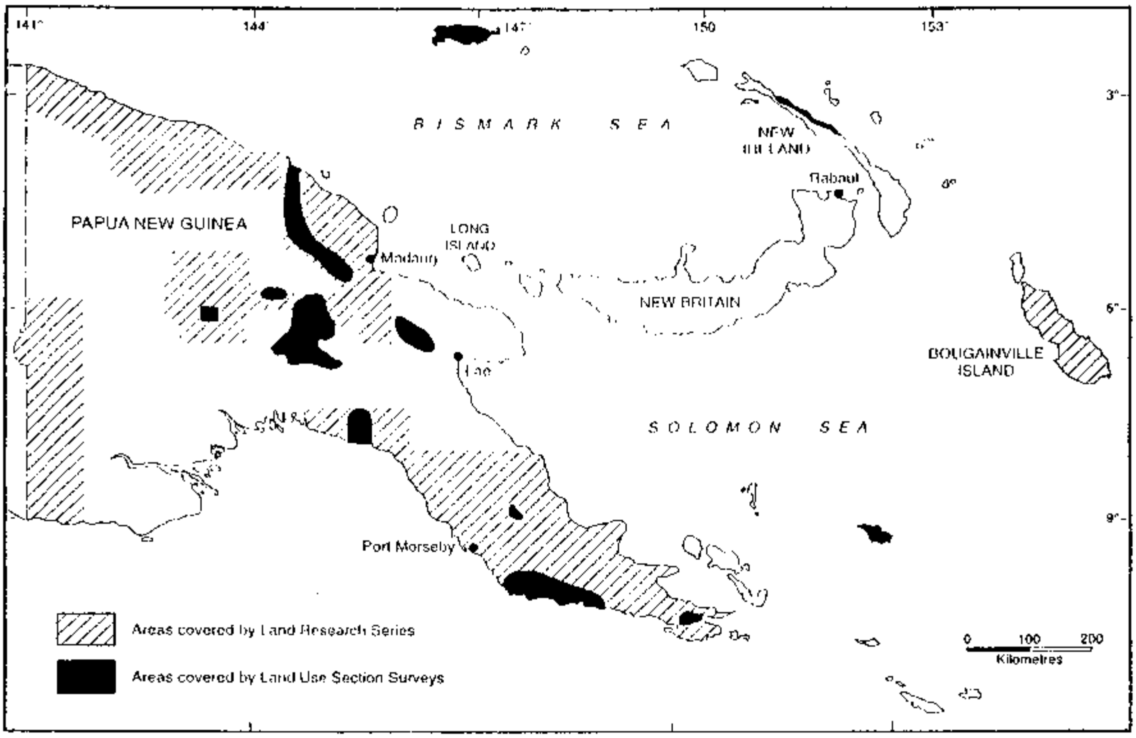
One of the major advances incorporated into PNGLES is the ability to use the PNG Resource Information System (PNGRIS). PNGRIS is a georeferenced data base of land resource information organised into spatial entities expressed at a scale of 1:0.5 M referred to as resource mapping units (RMU's) which are equivalent to polygons in GIS parlance (Bellamy 1986). PNGRIS is a development of CSIRO's land system mapping and PNG was possibly the first developing nation to have such a detailed data base that encompasses the whole country.[vii] Prior to this LSE could only be sensibly applied when detailed soil mapping was available. PNGRIS allowed the whole country or selected portions to be evaluated.

Built in to LCC and LSE are assumptions concerning the viability of particular land use practices mainly in terms of short term profitability. With a growing awareness of land degradation and the need to consider much more than short term profitability of farming practices the issue of sustainability has dominated the international land evaluation agenda during the 1990's. The Framework for Evaluating Sustainable Land Management (FESLM), which began appearing in draft form in 1991, is the latest land evaluation system designed to undertake this task at various management scales from individual fields to national level (Smythe and Dumanski 1993). The scheme is still being developed and trialed. FESLM and it is not without its critics. Brookfield and Humphreys (1994) noted that the structure was not particularly suited to complex multiple cropping systems widely used by subsistence farmers such as in PNG. They suggested that the agroecosystem scale was the appropriate lower level of FESLM-type investigation in these situations. Considerable work is required on this scheme and it is likely that investigations in PNG will assist this. In particular the main issue driving the Mapping of Agricultural Systems Project in PNG (MAPS) is the issue of the sustainability of these systems in the context of expected population growth, economic development, increased land degradation potential and global warming (Bourke *et al.* 1993). MAPS will use the FESLM approach to assist in this task and it is expected that this will also provide a means for scrutinising it (B.J. Allen pers comm).

LAND SYSTEMS MAPPING

No discussion on land evaluation would be complete without some comment on land systems mapping (LSM). Though much has been written about LSM in the international literature very little of it reflects the PNG experience. The process of undertaking a generalised assessment of the natural resources, including soil, over large tracts of little known terrain at a reconnaissance level was developed in Australia in the late 1940's. The land system approach aimed to delineate land that exhibited a recurring pattern in landform, soils and vegetation and was first applied to northern Australia by CSIRO (Christian and Stewart 1953). The same approach was soon applied to PNG with teams that included a pedologist, a geomorphologist, a plant ecologist/forester and others producing land system maps at scales of 1:0.25 to 1:0.5 M (Haantjens 1965; Blake and Paijmans 1973). Two important outcomes arose out of LSM in PNG. First, by the early 1970's about 40% of the country had been surveyed (Figure 1).[vii] This was a much higher proportion than the area mapped in Australia and more importantly it was reasonably representative though not all major agriculturally important areas were covered. This allowed the generation of separate 1:1 M maps on landforms, vegetation, soils, land use and forest types that covered the whole country. In turn these maps led to PNGRIS which forms the basic natural resource base for LSE as commented on above. The second point deals with the core concept of LSM. In Australia land systems could adequately represent large tracts of country and the concept of a recurring pattern between landform, soils and vegetation has held sacrosanct. This proved difficult to apply in PNG. Haantjens (1965) recognised three types of land system photo patterns in which mixtures of the last two are the most common: the truly 'recurring' pattern as noted above, the 'catenary' pattern, and an 'irregular' pattern. This change is not emphasised in the land system reports though it is apparent that a different concept is being applied if the reports and maps are carefully scrutinised. An outcome of this broadening of the land system concept was an even greater reliance on airphoto interpretation and the use of land-

***Figure 1.* Areas covered by CSIRO land system mapping and major surveys conducted by the PNG's Land Use Section and affiliates (modified from Humphreys 1991).**



forms or vegetation patterns depending on the terrain. Further difficulties emerged during a mapping exercise of Simbu Province in which the next level of detail in land system mapping was applied, *viz.* the land unit (Scott *et al.* 1985). They found it necessary to map on the basis of landform only when using a comparatively larger mapping scale of 1:0.1 M. The reason for these differences lies in the nature of the terrain: plate centre terrain of Australia compared to the much more tectonically active and higher relief plate margin terrain of humid PNG.

EROSION STUDIES

If published information is a guide, it is apparent that the first systematic treatment of soil erosion in PNG did not commence till the 1980's. At least this is what it must appear to outsiders. In reality the

Table 1. **Summary of denudation estimates in Papua New Guinea (modified from Blong and Humphreys 1992).**

Location & category	Material	Rate (mm 1000 y^{-1})	Source
*Geological rates (with limited accelerated rates) in mountainous terrain**			
Hydrographers Range	volcanic	80-750	Ruxton & McDougall (1967)
Mt Giluwe	volcanic	590	Loffler (1977)
Kaugel Basin	volcanic & sedimentary	270	Pain (1973)
Mts Toricelli & Bewani	granites & mixed sedimentary	1000-1430	Simonett (1967)
northern Chimbu	volcanic ash	< 60	Humphreys (1984)
Mixed accelerated and geological rates in mountainous terrain			
Vulcan (Rabaul)	volcanic - pumice	18000	Ollier & Brown (1971)
Mixed accelerated and geological rates from large drainage catchments			
Purari River at Wabo	mixed geology	790	Pickup *et al.* (1977)
Fly River	mixed geology	260-350	Picup *et al.* (1981)
Largely geological rates from small to moderate catchments			
Aura River	mixed geology	4190	Pickup (1977)
Ok Ningi	mixed geology	2980-4050	Pickup *et al.* (1991)
Ei Creek (Sogeri)	agglomerate	90	Turvey (1974)
Kuk swamp	volcanic ash	1.5	Hughes *et al.* (1991)
Accelerated rates			
road batters in northern Chimbu	Chim mudstone	46000-91000	Blong & Humphreys (1982)
Kuk swmap	volcanic ash	340	Hughes *et al.* (1991)
Bare erosion plots (on 20-45° slope)	volcanic ash & clay	3500-7500	Humphreys (1984)

* Geological denudation means the natural rate of surface lowering that would occur in the absense of human impact. As the name suggests accelerated denudation refers to the impact of man which normally leads to an increase in erosion.

situation was some what different. To newly arrived researchers the mountainous, humid tropical setting of much of PNG is a recipe for high levels of erosion: intense tropical storms, raging freshets of the uplands and weakly protected soils is a formula for guaranteeing rapid erosion. Those with more experience recognised that the evidence did not appear to match expectation and adopted a much more conservative approach and directed research towards plant nutrition. This approach appears to have persisted throughout much of the colonial time. By the late 1970's a dichotomy of opinion was apparent. The more conservative approach was still pursued by the well established DAL. In contrast very different viewpoints were espoused from within the Department of the Environment and from others including academic staff from the universities. To a certain extent the recent arrival syndrome was evident but there was also a sense that erosion, if not an issue now, would surely become one, as agricultural systems were forced to intensify under the combined effects of population growth and the need for cash income. This lead to the establishment of erosion experiments by DAL in the highlands (Humphreys 1984) and the lowlands (Tyrie unpublished). At the same time other smaller scale studies were undertaken (Williams 1981; Wood 1984, 1985; Carman 1989). Perhaps not unexpectedly the results of this research showed that many of the various opinions had merit. An outline of some of the major findings is presented below:

(i) In a general sense the levels of erosion are not as high as might normally be expected. What is meant by 'normal' is crucial to this discussion. Normal is not defined in any statistical sense. It is used in the context of expectations based on previous experience, perception and the literature.[ix] In particular, it was the opinion of senior officers and key decision makers that if erosion was widespread it would manifest itself as extensive rilling and perhaps gullying. They were not. Furthermore, there were few agricultural areas that were badly affected by erosion. In addition geomorphologists were uncertain as to the efficacy of various erosional processes in the forested humid tropics. This issue was subsequently examined in two different ways in PNG. Ruxton (1967) established the reality of slope wash under mature primary rainforest and Simonett (1967) showed by elaborate statistical analysis the importance of landslides in denudation in earthquake prone areas. Nevertheless, overall erosion levels in PNG appear to be slight to moderate using FAO guidelines[x] with high to very high levels recorded under particular circumstances such as following a major earthquake (Simonett 1967), emergence of a volcano (Ollier and Brown 1971), and on road batters in very erodible mudstones (Blong and Humphreys 1982) (Table 1).

(ii) The reasons for lower than expected soil loss was attributed to the soil characteristics, rainfall intensity and vegetation cover (Humphreys 1984). Moderately fertile, loamy to clayey topsoils with high organic matter and good structure are not conducive to erosion. The rainfall, whilst substantial, is not particularly erosive. Most of PNG is outside of the cyclone belt and has a wet and less-wet seasons rather than distinct wet/dry seasons as occur around Port Moresby. As a consequence vegetation growth is prolific throughout much of the year. Hence, torrential downpours are likely to strike a well vegetated surface rather than bare ground. Existing data from micro plots and garden plots indicated that moderate soil loss (up to 50 t ha^{-1} y^{-1}) could be expected on totally bare ground on slopes up to 30° but reduces to low levels (<10 t ha^{-1} y^{-1}) as ground cover increased beyond about 50 % as occurs during most of the cropping cycle (Figure 2). Subsequently DAL initiated a much more rigorous set of erosion plot experiments at Aiyura and Kerevat as part of a network of trials conducted as part of the Pacificland project by the International Board of Soil Research and Management. Results to date appear to substantiate earlier findings (B.M. Wayi pers com; Humphreys 1994).

(iii) Major increases in soil loss have been determined from sedimentation rates in a few archaeological sites using enclosed swamp and lacustrine deposits (e.g. Golson 1982; Oldfield *et al.* 1985; Gillieson *et al.* 1987; and Hughes *et al.* 1991). The best studied site occurs at Kuk in the upper reaches of the Wahgi valley in WHP (Figure 3). Under apparently undisturbed forest prior to 9000 years ago annual denudation average only 0.012 tonnes ha^{-1} (1.5 mm 103 $years^{-1}$). This increased 8-14 fold to 0.1 - 0.17 t ha^{-1} y^{-1} (12-21 mm 103 y^{-1}) with the onset of dryland cultivation Under present cultivation practices - a mixture of old and new techniques involving more intensive land use and metal tools (to support a higher population density), soil loss is about 2.7 t ha^{-1} y^{-1} (340 mm 103 y^{-1}) (Hughes *et al.* 1991). Though this remains a very low rate of soil loss by global standards (FAO 1978), it is two

Figure 2. **Soil loss versus slope from microplots and garden plots on andisols and tropepts. Al but Carman's study is from the central highlands. Modified from Humphreys and Wayi (1990).**

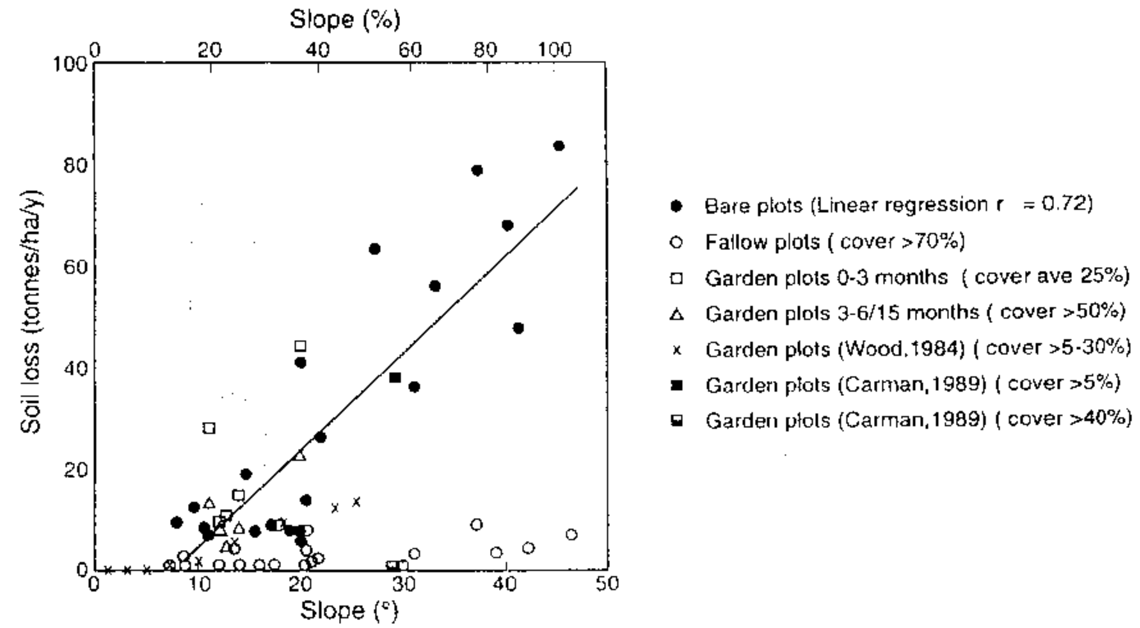
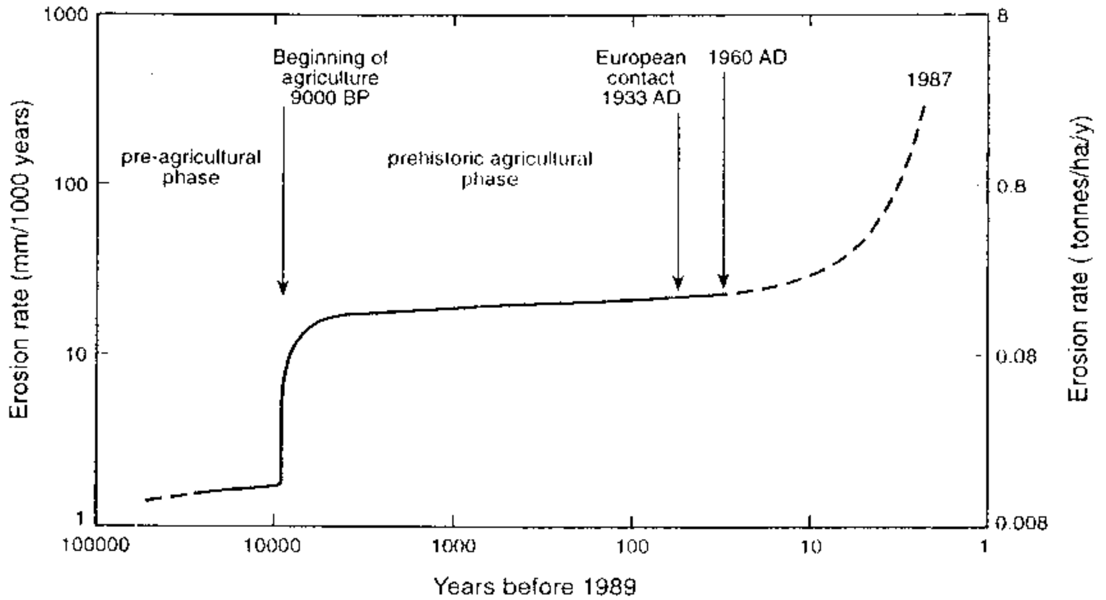


Figure 3. **Long term soil loss rates based on sedimentation in a swampy site at Kuk near Mt. Hagen. Modified from Hughes *et al.* (1991).**



orders of magnitude greater than the natural (pre 9000 years ago) rate. On this basis it becomes necessary to question the longer term sustainability of the current situation though Hughes *et al.* (1991) argue that it is a very robust system.

SOIL CONSERVATION

By the 1970s the most publicised account of soil erosion was based on research conducted in southern Africa, USA and to a lesser extent in Australia. This confirmed that increases in soil loss could be expected on unprotected soil. Furthermore, the only parameter that could be modified or even controlled by management practices was ground cover. In drier environments the basic soil conservation strategy to emerge was to retain water on hillslopes to encourage vegetation growth. This became the golden rule of soil conservation (e.g. Hudson 1971) and it remains so today. This notion was applied to the PNG highlands (Herman 1977; Gagne 1977) and advocated at least informally by many others. However, it was apparent to others that the main conservation strategy in humid areas of PNG was to remove water from hillslopes without causing erosion. Because of the high rainfall prolific vegetation growth occurred without the need to trap water on hillslopes. Furthermore, an examination of traditional soil conservation methods showed that controlled water shedding is widespread in PNG especially where heavy clay soils occur. In this situation a system of shallow drains (barets), aligned both down and across slope, are often employed to remove excess water, even on hillslopes up to 20° (Wood and Humphreys 1982; Humphreys and Wayi 1990). On steeper slopes a variety of barriers are sometimes placed across the slope. These act to trap soil and reduce velocity of runoff though it seems that the primary purpose is not related to conservation but to the mark out sections of the garden.

As noted above traditional soil conservation strategies are widespread in PNG. However, they remain poorly documented and understood. A review by Wood and Humphreys (1982) describes an array of techniques designed to overcome a common range of problems. For example the cultivation of sweet potato in poorly drained soils necessitates aerating the soil and this is achieved by drains and/or raised beds and/or mounds. Any combination of these three techniques may be found through out the highlands. A considerable amount of information has been gained in the study of agricultural practices especially by anthropologists and human ecologists but little of it has been seriously evaluated by researchers trained in agricultural science in general or soil science in particular."

SOIL FERTILITY STUDIES

Considerable effort has been expended in PNG by soil scientists and especially agronomists in examining crop response to major and trace elements so as to determine the most suitable fertiliser dose to rates. An extensive literature exists on this (see Bourke 1993) but this is not reviewed here. Despite this, however, only very generalised accounts exist on the fertility status of various soil types (see Bleeker 1983 for a useful treatment). One of the issues that needs to be confronted is that a particular chemical characteristic is not always restricted to a particular soil type and the converse that the same soil type may exhibit very different chemical properties. For example boron deficiencies appears to occur in several soil types including volcanic ash soils in the highlands but not all ash soils exhibit this problem. In other situations a clearer association exists. Phosphate fixation is widespread in highland ash soils (Parfitt and Mavo 1975; Moody and Radcliffe 1986) and a strong variable charge quality is expected (Radcliffe and Gilman 1985; Bleeker and Sageman 1990) though again neither property is restricted to the ash soils.

One issue that may hinder our understanding of the fertility status of soils reflects the practice of obtaining standard soil chemical tests on representative soil profiles during the course of a soil survey. These data are used to provide an overall assessment noting any apparent deficiencies and toxicities that might affect crop growth. For many years the guidelines developed by Metson (1956) in New Zealand have been applied. This appears to have worked reasonably well. It will be some time before a truly in house rating scheme can be devised given the large number of crops and cultivars grown in PNG even though useful advances in this direction have been achieved with crop suitability ratings noted above. Detail information is mostly limited to plantation crops such as cocoa, copra, oil palm, tea and coffee where suitable trials have been conducted. However, a major difficulty in assessing spot samples, as undertaken during normal surveys, is that the results relate to the time of sampling so that the relationship to site history remains obscure. Sampling sequentially so as to evaluate temporal effects is fairly common in plantation crops and during the course of agricultural field trials but only in a few cases has it been attempted in traditional cropping systems. Nevertheless, successional changes have been attempted in which the change in nutrient level is assessed during cropping, fallow and forest regrowth phases following the example set by Nye and Greenland (1960) in Africa (e.g. Clarke and Street 1967; Manner 1969,1976; Wood 1979, 1984; Humphreys 1984). These studies follow an ergodic approach (i.e. the substitution of space for time) and sample adjacent areas under different stages in the cultivation cycle simply because it is much too impractical to conduct a trial over 10-50 years or more. This approach indicates the most appropriate length of fallow (= recovery period) which remains essential information for assessing sustainability. A particularly interesting variation of this type of research was undertaken by Wood (1984). He utilised a very detailed oral history in the Tari Basin to date individual gardens to determine changes in nutrient levels and sweet potato yields under continuous cultivation.[xii] Yield decline on fertile soils adjacent to swamps and on floodplains (tropepts and fluvents) remained <20% after 100 years of cultivation whereas volcanic ash soils suffered a 50% decline in <50 years (Figure 4). Apart from general soil chemical attributes it is also appropriate to utilise other parameters such as soil microbial activity which is thought to provide a much more sensitive indicator of nutrient decline and recovery. Sparling and Humphreys, (1991) used microbial carbon values on garden, fallow and forest soils in the upper Chimbu valley at 2700 m a.s.l. and found that recovery period may exceed 50 years. Much more research of this type is required on a variety of soil types and cropping systems.

Another issue that has not been addressed is the biogeochemical link between the topsoil and deep subsoil. Often the whole soil (i.e. topsoil, subsoil and parent material) is treated as a discrete unit

Figure 4. **Decline in sweet potato yields over time on various soil types in the Tari Basin (modified from Wood 1985)**

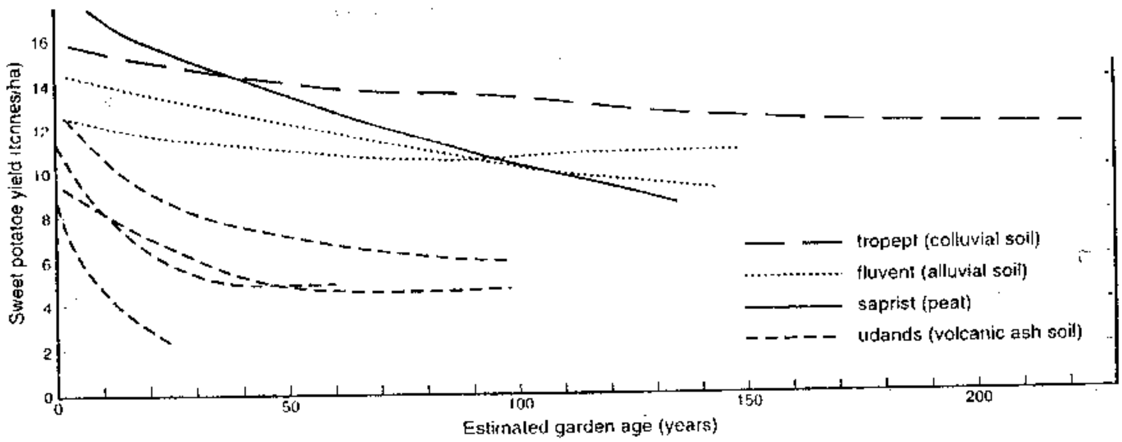
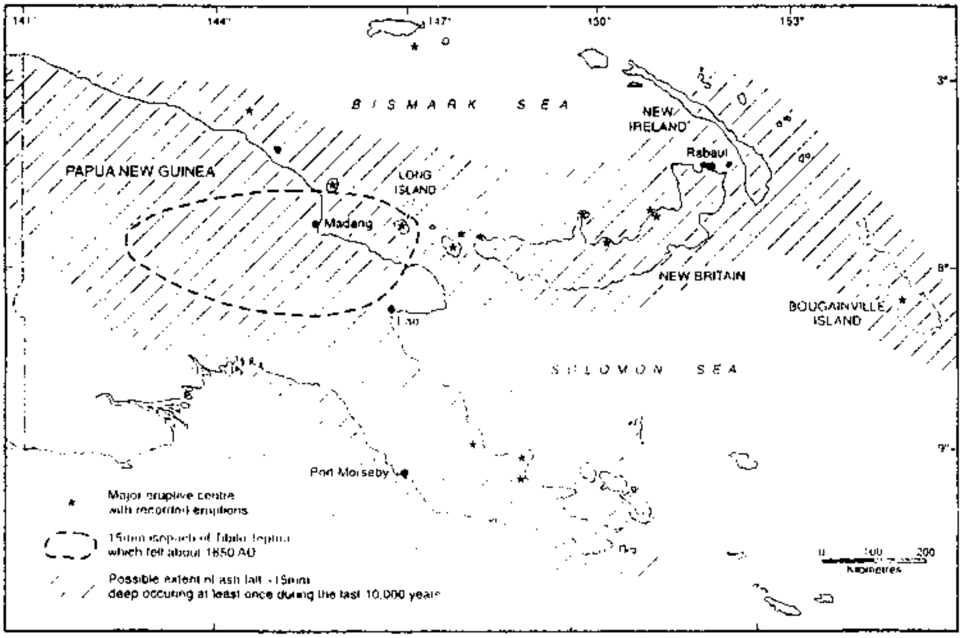


***Figure 5.* Known extent of PNG where >15 mm of ash probably landed during the Holocene. The known extent of the well dated and mapped Tibito tepha is also indicated.**



and chemical changes are assessed on the implied assumption that the topsoil and subsoil is derived from the same parent material. It is apparent that this assumption does not always hold. Topsoil enrichment by volcanic ash has probably had a major effect and it is likely that about half of PNG soils, have received over 15 mm of ash during the last 10,000 years (Figure 5).[xiii] Similarly, extensive colluvial mantles occur, even on gentler slopes, and in various situations the overlying material is derived from a different lithology as is often recognised with mobile mantles (Paton *et al.* 1995; Ollier and Pain 1996) or other transported materials as has been speculated to occur in texture contrast soils in Irian Jaya (Schroo 1964) and on the Fly Platform (Bleeker 1983). In this situation chemical and mineralogical differences can be expected. However, downslope transport is not limited to mineral grains. Ruxton (1967) recognised the movement of litter and other organic fragments as part of slope wash under mature primary forest. Other well stratified deposits such as alluvium may also show chemical and mineralogical differences but where the source area is the same, any chemical variations may be related to particle size effects as would be expected if lithic sands were compared to clayey materials providing of course that allowance is made for the influence of organic matter. In thicker volcanic ash mantles trace element differences exist between successive ash layers even when they are derived from the same volcano and this feature provides the basis for fingerprinting individual layers.

It is possible that some of the mechanisms used to explain chemical trends such as the intensity of weathering and water table fluctuations may require reinterpretation though this task becomes difficult if the background information on the soil and the site is inadequate. For example, high ratios of exchangeable magnesium to exchangeable potassium are reported in soils in south-eastern PNG especially on the southern side of the Owen Stanley Range to the east of Port Moresby (Best 1977). This may be attributed in part to the ultramafic rocks in the hinterland which also have high magnesium. Just why magnesium accumulates here despite the high rainfall (high leaching rate) is not fully understood. The situation is somewhat confused since the same high ratios are not as common in soils on the north coast which also drains ultramafic areas though further west near Madang magnesium rich soil occurs with dunite (Holmes and Hall 1976). Perhaps the addition of volcanic materials on the north coast masks the high magnesium though it is also possible that a lack of knowledge of the real distribution of magnesium rich soils contributes to the problem. In addition to high magnesium levels the same ultrabasic rocks in eastern Papua reveal high and even toxic levels of manganese and cobalt which appear to concentrate in the topsoil above the seasonal high water table level (Bleeker and Austin 1970) though given the issues raised above other explanations should be evaluated.

The above discussion is from the viewpoint of seeking to understand soil fertility status and response on the basis of soil type. However, other vectors may be important too. For example during smaller ENSO droughts of 1972 and 1982 it appeared that there is a net build up in nutrient reserves so that the post drought period often produces a growth flux (R.M. Bourke pers com). The reasons for this have not been completely evaluated but nutrient release following fire, reduced rates of decomposition and reduction in weeds and pests are possible contributing factors. Similarly, it is not known whether a similar effect will occur after the pronounced 1997 drought. This is an area where soil scientists can and should make a significant contribution.

SOIL AND HEALTH

A direct association between soils and public health is often difficult to establish but it has been widely recognised throughout the world that land degradation is an important factor leading to population decline. The presence of extensive grasslands in Papua New Guinea, especially in areas where forest might normally be expected, is often ascribed an anthropogenic origin that involved a combination of clearance for cultivation and fire (e.g. Robins 1960). More detail on what may have transpired in the past has been obtained from various late Quaternary deposits especially those that show direct evidence of cultivation (e.g. Golson and Hughes 1980; Gillieson *et al.* 1987; Hughes *et al.* 1991). The deposits often show substantial increase in sedimentation in pre-historic times (mostly in the last 6000 years). Various lines of evidence have been employed to indicate that the sediment was derived from cultivated land in the contributing catchment and not from localised reworking of valley fills. The emerging scenario is that the lower productivity grasslands, especially on steeper slopes, were subjected to excessive soil erosion and hence the loss of an important soil nutrient store (i.e. the topsoil). A sequence of forest clearance for cultivation, over use of the soil, fertility decline and erosion would lower soil productivity and lead to extensive grasslands. The use of fire, possibly aided by ENSO driven droughts such as occurred over much of PNG in 1997, would assist in maintaining these grassland and also explain the low population densities that are common today.[xiv]

Other links to public health have been suggested also. A high incidence of motor neuron diseases such as Amyotrophic Lateral Sclerosis and Parkinson-Dementia have been found in communities using soils containing high levels of Al, Fe and Mn and low amounts of Ca, Mg and Zn (Standal 1988). This is a feature of the so called acid soils i.e. soils of moderately low pH (normally <5.5) with high levels of available aluminium and manganese that may be toxic to plants. A preliminary assessment of the distribution of acid soils in PNG indicated that about 11% of the country may contain acid soils but that these areas support only about 2% of the population (Humphreys and Freyne 1988). However, whether or not this relationship is due to the low fertility status of these soils or to various diseases is not known for certain even though it appears to be the case amongst certain groups in Irian Jaya. Soil, especially clay, is used as a medicine sometimes. The practice of eating clay, or geophagia, is reported in the East Sepik (Drover and Borrell 1980) but it is probably much more widespread in PNG. It appears that clay may provide an additional source of essential minerals such as in the smectite dominated Sepik samples which are favoured by pregnant women. Clays are also used for antidiarrhoeal and detoxification purposes (Reid 1992) in which case kaolinite is preferred.

LATOSOLS AND TROPICAL WEATHERING

One of the most enduring themes in soil science that emerged during the first half of this century was the belief that something different happens under tropical conditions. Intense or mature weathering and leaching under warm humid conditions was thought to lead to laterisation (= ferrallisation) i.e. the concentration of iron and aluminium oxides/hydroxides and kaolinite at the expense of silica. This theme was adopted by Humbert (1948) who used an example from near Oro Bay to promote a general theory of laterisation.[xv] In particular he advocated that laterites develop best under tropical wet and dry conditions and suggested that the lowland grassland environments would prove most conducive, thus implying that laterites (= latosols or oxisols) would be widespread in lowland PNG. Subsequent investigations indicated that the products of intense weathering, leaching and new mineral formation were fairly unusual in PNG (Haantjens and Bleeker 1970) and that latosolic soils (mostly oxisols) occupied only 5-10% of the country with occurrences confined mostly to a few areas such as near Safia (close to Humbert's site) and in Western Province (Bleeker 1972 1983; Bleeker and Sageman 1990) and also at some ore mineralisation sites of limited extent (e.g. Holmes and Hall 1976). It also became apparent that these soils occurred under rainforest in more humid settings (>2000 mm) than that suggested as being optimal by Humbert (1948). This finding meant either that the climatic conditions needed broadening to span the humid to wet/dry tropics or that some type of climatic change was required to account for those occurrences not conforming to the theory. Not withstanding the potential for circular argument Humbert (1948) opted for the latter. Of course, it is possible that other factors might be more important than climate but this option does not appear to have been considered in any serious manner.[xvi] Nevertheless, despite these misgivings it was widely accepted that laterite soils in PNG, especially deep varieties (i.e. more than a few metres thick) required a long time to form and hence would be preserved on remnants of old landscapes that had remained stable long enough for a latosol to form.

At face value this appeared to be plausible and conformed with ideas developed elsewhere that laterites take around 105 to 106 years to develop and that the tectonically active quality of the PNG landscape was not conducive to latosol development (e.g. Haantjens and Bleeker 1970; Bleeker 1972; Bleeker and Sageman 1990). However, the available information on age, though very limited, provides a very confusing picture. A carbon-14 age of 27,000 y BP was obtained from the upper few metres of the Lake Murray Beds on the Fly Platform (Blake and Ollier 1971) at a site that contains various latosols (oxisols) and associated soils. This very young age presents a dilemma: either the soil was missidentified (i.e. it is not really a latosol), or the date is erroneous (i.e. much too young), or that the implied great age requirement is not necessary. In contrast, other studies in PNG concerned with the alteration of volcanic ash, a highly reactive and easily weatherable medium, requires thousands of years to register a pronounced effect. Ruxtcn (1968) found only slight etching of hornblendes in tephras <20,000 years old and the transformation of allophane to halloysite can occur within a few thousand years (Bleeker and Parfitt 1974). It is possible that a simpler explanation may suffice to explain these soils: that they occur in localised situations conducive to the formation and preservation of deep weathering mantles such as thicker clay bands, oxidized metaliferous rocks, hydrothermal alteration zones, areas with a denser network of joints, and other easily weathered lithologies such as ultra-mafic rocks. The study by Bleeker and Sageman (1990) is instructive on this issue. They compared two deep latosols (acrorthox and eutrorthox) near Safia. The former had developed in serpentinite, an ultra basic rock low in silica with comparatively high magnesium, and it was shown to be composed mostly of goethite rather than clay minerals. The latter had formed in basalt and was dominated by 1:1 lattice clay minerals with greater variable charge properties. This implies that it is the rock type or the lithological material that retains a strong controls on soil mineralogy and hence soil type. A similar point was used to explain major differences in surface charge properties between nominally similar soils (Gilman and Sinclair 1987). In addition, it is now widely recognised that if there are any differences between temperate and tropical weathering regimes it is in the speed of alteration, especially the through-put of water, and not the type of mechanism involved.

CONCLUSIONS

This paper commenced with the fairly modest aim of revealing something of the variety of soil studies that have been undertaken in PNG and at the same time provide some background as to why various themes were addressed. The major limitation with this approach is that some important topics such as the investigations into soil nutrient deficiencies and toxicities were omitted or hardly addressed at all. Neverthless, some very real advances have been achieved and these are identified in the text.

In preparing this review it became evident that it is not so much the variety of soil themes investigated that is of major interest but rather the diverse backgrounds of the investigators in terms of both nationalities and disciplines. Even so, no attempt was made to link opinions and approaches or even paradigms to cultural or disciplinary roots. A natural consequence of this is the divergence of opinion, and aspects of this are evident in the paper. This healthy effect is also enhanced by the policy to send most PNG soil scientists overseas for postgraduate studies. In this respect it is apparent that many of the investigated themes benefited from the contribution of two major approaches: present day dynamics and environmental history. Thus an understanding of erosion comes from process studies and the depositional records, sometimes spanning thousands of years. Likewise an understanding of nutrient decline and recovery was obtained from experimental plots and utilising old gardens dated by oral history. In a similar way it is necessary to understand local land use history and the source of soil materials to adequately interpret soil chemical trends and other issues such as sustainability.

ACKNOWLEDGMENTS

In composing this paper I have relied on conversations and tit-bits of information gleaned from various sources in an attempt to mould it into something more than just a straight review. Accordingly, I acknowledge the assistance of various PNG workers who have contributed in some way to this retelling of an incomplete history. For convenience they are named here on an alphabetical first name basis: Andrew Wood, Balthasar Wayi, Bryant Allen, David Freyne, Grahme Tyrie, John McAlpine, Michael Bourke, Paul Harding, Pieter Bleeker, Ralph Scott, Robin Hide, Russell Blong and many others. Of course any inaccuracies must rest with me.

REFERENCES

ALLBROOK, R.F. and **RADCLIFFE, D.J.** (1987). Some physical properties of andepts from the Southern Highlands, Papua New Guinea. *Geoderma*. 41. 107-121

ALLEN, B.J. and **BOURKE, R.M.** (1997). Report of an assessment of the impacts of frost and drought in Papua New Guinea. Australian Agency for International Development. (mimeo) 21 pp.

ANON (1983). Soil classification and agrotechnology transfer for agricultural development. Fifth international forum on soil taxonomy and agrotechnology transfer. 24 April-6 May, 1983, Papua New Guinea

ATKINSON, G. (1993). Soil materials, a layer based approach to soil description and classification. *Catena* 20:411-419

BELLAMY, J.A. (1986). Papua New Guinea Inventory of Natural Resources, Population Distribution and Land Use Handbook. CSIRO (Aust) Division of Water and Land Resources, Natural Resources Series No. 6. (CSIRO: Melbourne)

BEST, E.K. (1977). A study of potassium in a Papuan alluvial soil. M.Sc. Thesis, University of Papua New Guinea, Port Moresby.

BLAIKIE, P. and **BROOKFIELD, H.C.** (1987). Land degradation and society. Methuen, London

BLAKE, D. H. and **OLLIER, C. D** (1971). Alluvial plains of the Fly River, Papua Zeit. *Geomorphologie* 12:1-17

BLAKE, D.H. and **PAIJMANS, K.** (1973). Reconnaissance mapping of land resources in Papua New Guinea. *Aust. Geog. Stud.* 11:201-210

BLEEKER, P. (1972). The mineralogy of eight latosolic and related soils from Papua New Guinea. *Geoderma* 8:191-205

BLEEKER, P. (1975). Explanatory notes to the land limitation and agricultural land use potential map of Papua New Guinea. Land Research Series No. 36. CSIRO, Melbourne.

BLEEKER, P. (1983). Soils of Papua New Guinea. CSIRO/ ANU Press, Canberra

BLEEKER, P. and **AUSTIN, M.P.** (1970). Relationships between trace element contents and other soil variables in some Papua New Guinea soils as shown by regression analysis. *Aust. J. Soil Res.*, 8,133-43

BLEEKER, P. and **FREYNE, D.F.** (1981). Areas Suitable for Cocoa Production in Papua New Guinea. CSIRO and Dept. Primary Industry (PNG).

BLEEKER, P. and **PARFITT, R.L.** (1974). Volcanic ash and its clay mineralogy at Cape Hoskins, New Britain. *Geoderma* 11,123-135

BLEEKER, P. and **SAGEMAN, R.** (1990). Surface charge characteristics and clay mineralogy of some variable charge soils in Papua New Guinea *Aust. J. Soil Res.* 28:901-917

BLONG, R.J. (1982) A Time of Darkness. Australian National Univ. Press, Canberra.

BLONG, R.J. and **HUMPHREYS, G.S.** (1982). Erosion of road batters in Chim shale, Papua New Guinea. Civil Engng. Transact. I.E. Aust., CE24, No. 1.

BLONG R. J. and **PAIN, C.F.** (1976). The nature of highland valleys, central Papua New Guinea. *Erdkunde* 30:212-217

BLONG R. J. and **PAIN, C.F.** (1978) Slope stability and tephra mantles in the Papua New Guinea highlands. *Geotechnique* 28:206-210

BOURKE, R.M. (1993). Bibliography of soil fertility and plant nutrition in Papua New Guinea. Papua New Guinea. DAL Tech Rept 93/1

BOURKE, R.M., HIDE, R.L., ALLEN, B.J., GRAU, R., HUMPHREYS, G.S. and **BROOKFIELD, H.C.** (1993). Mapping agricultural systems in Papua New Guinea. In: T. Taufa and C. Bass (eds) Population Family Health and Development. University of Papua New Guinea Press. pp 205-224

BRASHER, L.R., TRANGMAR, B.B. and **RIJKSE, W.C.** (1995). Handbook for land resource survey methods in Papua New Guinea. PNGRIS Report No. 1

BROOKFIELD, H.C. and **BROWN, P.** (1963). Struggle for land: agriculture and group territories among the Chimbu of the New Guinea highlands. Oxford Univ. Press, Melbourne.

BROOKFIELD, H.C. and **HUMPHREYS, G.S.** (1994). Evaluating sustainable land management. Are we on the right track? Proc 15th World Congress of Soil Science, Acapulco, Mexico. Vol 6 a:388-397

BRUNE, G.M. (1949). Notes on soils, erosion and sediment production in the southwest Pacific area. Proc. *Soil Sci. Soc. Amer.* 14,395-398

CARMAN, K.L. (1989). Soil loss and runoff from demonstration gardens in Matalau Village East New Britain Province. DAL (PNG) Tech. Rpt. 89/4. 19 pp

CHARTRES, C.J. and **PAIN, C.F.** (1984). A climosequence of soils on late Quaternary volcanic ash in highland Papua New Guinea. *Geoderma* 32:131-155

CHARTRES, C.J., WOOD, C.J., A.W. and **PAIN, C.F.** (1983). The development of micromorphological features in relation to some mineralogical and chemical properties of volcanic ash soils in highland Papua New Guinea. *Aust. J. Soil Res.*, 23:339-354

CHRISTAIN, C.S. and **STEWART, G.A.** (1953). General Report on Survey of the Katherine-Darwin Region, 1946. CSIRO (Aust) Land Research Series No 1. (CSIRO. Melbourne).

CLARKE, W.C. and **STREET, J.M.** (1967). Soil fertility and cultivation practices in New Guinea. *J. Trop. Geog.*, 24,7-11

DEARDEN, P.N., FREYNE, D.F. and **HUMPHREYS, G.S.** (1986). Soil and land resource surveys in Papua New Guinea. *Soil Surv. & Land Eval.* 6,43-50

D'SOUZA, E.J. and **BOURKE, R.M.** (1986). Intensification of subsistence agriculture on the Nembi Plateau, Papua New Guinea. 2. Organic fertilizer trials. *PNG J. Agric., For. & Fish.* 34:29-39

DROVER, D.P. and **BORRELL, O.W.** (1980). Analysis of two edible clays from East Sepik, Papua New Guinea. *Science in New Guinea* 7:6-11

FOOD and AGRICULTURE ORGANISATION. (1976). A Framework for Land Evaluation. Soils Bulletin No 32. FAO. Rome

FOOD and AGRICULTURE ORGANISATION. (1978). Report on the FAO/UNEP expert consultation on methodology for assessing soil degradation. Project No. 1106-75-05. FAO, Rome.

FOURNIER, F. (1960). Climat et erosion; la relation entre l'erosion du sol l'eau et les Precipitations atmospheriques. Presses Univ., Paris

GAGNE, W.C. (1977). Entomological investigationsof agrosilverculture using composted contour mound method in Papua New Guinea. *Science in New Guinea* 5:85-101

GILLMAN, G. P. and **SINCLAIR, D.F.** (1987). The grouping of soils with similar charge properties as a basis for agrotechnology transfer. *Aust. J. Soil Res.* 25,275-285

GOLSON, J. (1982). Kuk and the history of agriculture in the New Guinea highlands. In R.J. May and H. Nelson (eds) Melanesia: beyond diversity. Vol. 1. ANU Press, Canberra. pp 297-307

GOLSON J. and **HUGHES P.** (1980). The appearance of plant and animal domestication in New Guinea. *Journal de la Soiètè des Océanistes* 36:294-303

GOODBODY, S. and **HUMPHREYS, G.S.** (1986). Soil chemical status and prediction of sweet potato yields. *Tropical Agriculture* (Trinidad) 63,209-211

GILLIESON, D., GORECKI, J., HEAD, J. and **HOPE, G.S.** (1987). Soil erosion and agricultural history in the central highlands of Papua New Guinea. In: V. Gardiner (ed) International Geomorphology 1986 Part II. John Wiley & Sons, Chichester. pp 507-522

HAANTJENS, H.A. (1963). Land capability classification in reconnaissance surveys in Papua New Guinea. *J. Aust. Inst. of Agric. Sci.* 29:104-107.

HAANTJENS, H.A. (1965). Practical aspects of land system surveys in New Guinea. *Journ. Tropical Geography* 21.12-20

HAANTJENS, H.A. (1969) Agricultural Land Classification for New Guinea Land Resources Surveys. 2nd rev ed. CSIRO (Aust) Division of Land Research Tech. Mem. No. 86/4. (CSIRO Canberra)

HAANTJENS, H.A. (1975). Procedures for computer staorage of soil and landscape data from Papua New aguinea. III. Input of soil site characteristics. *Geoderma* 13,129-139

HAANTJENS, H.A. and **BLEEKER, P.** (1970). Tropical weathering in the Territory of Papua New Guinea. *Aust. J. Soil Res.* 8:157-177

HAANTJENS, H.A. and **BLEEKER, P.** (1975). Procedures for computer staorage of soil and landscape data from Papua New aguinea. II. Input of soil capability and soil classification data. *Geoderma* 13,115-128

HAANTJENS, H.A.,BLEEKER, P. and **COOK, L.G.N.** (1975). Procedures for computer staorage of soil and landscape data from Papua New aguinea. I. General introduction and input of descriptive soil observation data. *Geoderma* 13,105-113

HAANTJENS, H.A. and **RUTHERFORD, G.K.** (1964). Soil zonality and parent rock in a very wet tropical mountain region. Trans. 8th Intern. *Congr. Soil Sci.* 5,493-500

HARDING, P.E., BLEEKER, P. and **FREYNE, D.F.** (1986). A handbook for land suitability evaluation for rainfed arabica coffee production in Papua New Guinea. Coffee Research Report No. 3. PNG Coffee Research Institute.

HARDON, H. J. (1938). Podsol profiles in the tropics. *Natuurkundig Tijdschrift voor Nederlandsch-Indie* 96,25-41

HARTLEY, A.C., ALAND, F.P. and **SEARLE, P.G.E.** (1967). Soil Survey of West New Guinea, the Balima-Tiauru Area. Soil Survey Report No. 1 (DASF: Port Moresby).

HEARN, G.J. (1995). Landslide and erosion hazard mapping at Ok Tedi copper mine, Papua New Guinea. *Quart. J. Engin. Geol.*, 28,47-60

HERMAN, M.L. (1977). Contour mounding - effective erosion control. In: B.A.C. Enyi and T. Varghese (eds) Agriculture in the tropics. University of Papua New Guinea. Port Moresby. pp 44-45.

HOLMES, K.D. and **HALL, R.J.** (1976). Marum nickeliferous laterite, Madang District, P.N.G. In: C.L. Knight (ed) Economic geology of Australia and Papua New Guinea - 1. Metals. Aust. Inst. Min. Metall. Monograph 5. pp 1011-1017

HUDSON, N. (1971). Soil Conservation. B.T. Batsford Ltd, London

HUGHES, P.J., SULLIVAN, M.E. and **YOK, D.** (1991). Human-induced erosion in a highlands catchment in Papua New Guinea: the prehistoric and contemporary records. Zeitschrift für *Geomorphologie* N.F. 83:227-239

HUMBERT, R.P. (1948). The genesis of laterite. Soil Sci. 65:281-190 Humphreys, G.S. (1984). The Environment and Soils of Chimbu Province, Papua New Guinea with Particular Reference to Soil Erosion. Department of Primary Industry (PNG) Research Bulletin No. 35. (DPI: Port Moresby).

HUMPHREYS, G.S. (1984). The Environment and Soils of Chimbu, Papua New Guinea with particular reference to Soil Erosion. Department of Primary Industry (PNG) Research Bulletin No. 35. (DPI: Port Moresby).

HUMPHREYS, G.S. (1991). Soil Maps of Papua New Guinea: a review. *Science in New Guinea* 17:77-103.

HUMPHREYS, G.S. (1994). The interpretation of soil erosion measurements. In: D. Howlett (ed) The management of sloping lands in the South Pacific Islands. IBSRAM (International Board for Soil Resesearch and Management)/Pacificland, Bangkok. Network Document no. 10. pp 111-138

HUMPHREYS, G.S. and **FREYNE, D.F.** (1988). Acid soils in Papua New Guinea. In: J.L. Demeterio and B DeGuzman (eds) Proceedings 3rd International Soil Management Workshop on the Management and Utilization of acid soils of Oceania. University of Guam. pp 28-38

HUMPHREYS, G.S. and **WAYI, B.M.** (1990). Measuring soil erosion on steep lands: the Chimbu experience. Pacificland Workshop on the establishment of soil management experiments on sloping lands. International Board for Soil Research and Management. IBSRAM Tech. Notes No. 4, 243-269

KANUA, M.B. (1995). A review of properties, nutrient supply , cultivation and management of volcanic soils, with particular reference to Papua New Guinea. *PNG J Agric., For. & Fish.*, 38:102-123

KLINGBIEL, A.A. and **MONTGOMERY, P.H.** (1961). Land capability classification. Agricultural Handbook No. 210. Soil Conservation Service, US Dept. of Agriculture.

LANDSBERG, J. and **GILLIESON, D.S.** (1980). Toksave bilong graun:common sense or empiricism in folk soil knowledge from Papua New Guinea. *Capricornia* 8:13-23

LÖFFLER, E. (1977) Geomorphology of Papua New Guinea. CSIRO and ANU Press, Canberra

MABBUTT, J.A. and **SCOTT, R.M.** (1966). Periodicity of morphogenesis and soil formation in a savanna landscape near Port Moresby, Papua. Zeit. *Geomorph.* 10, 68-89

MACFARLANE, M., TYRIE, G. and **HUMPHREYS, G.** (1990). Mineralogical studies of high phosphate soils from coral atolls of Milne Bay Province, Papua New Guinea. DAL Tech Rept. 90/3

MANNER, H.I. (1969). The effects of shifting cultivation on some soil properties of the Bismark Mountains. M.Sc. Thesis, University of Hawaii.

MANNER, H.I. (1976). The effects of shifting cultivation and fire on vegetation and soils in the montane tropics of New Guinea. Ph.D. Thesis, University of Hawaii.

METSON, (1956). Methods of chemical analysis for soil survey samples. New Zealand Soil Bureau Bulletin 12. 208 pp.

MOODY, P.W. and **RADCLIFFE, D.J.** (1986). Phosphorus sorption by andepts from the Southern Highlands of Papua New Guinea. Geoderma, 37,137-147

OLDFIELD, F., APPLEBY, P.G. and **THOMPSON, R.** (1980) Palaeoecological studies of lakes in the highlands of papua New Guinea. *J. Ecology*, 68,457-477

OLDFIELD, F., WORSLEY, A.T. and **APPLEBY, P.G.** (1985). Evidence from lake sediments for recent erosion rates in the highlands of Papua New Guinea. In: I. Douglas and T. Spencer (eds) Environmental change and tropical geomorphology. George Allen & Unwin, London.

OLLIER, C.D. and **BROWN, M.J.F.** (1971). Erosion of a young volcano in New Guinea. Zeit. *Geomorp.* 15,12-28

OLLIER, C.D. and **PAIN, C.F.** (1996). Regolith soils and landforms. John Wiley and Sons, Chichester Pain, C.F. (1973). The late Quaternary geomorphic history of the Kaugel Valley, Papua New Guinea. PhD thesis, Aust. Nat. Univ.

OLLIER, C.D., DROVER, D.P. and **GODELIER, M.** (1971). Soil knowledge amongst the Buruya of Wonenara, New Guinea. *Oceania* 42, 1:33-41.

PAIN, C.F. (1973). The late Quartenary geomorphic history of the Kaugel Valley, Papua New Guinea. PhD thesis, Aust. Nat. Univ.

PAIN, C.F. and **BLONG, R.J.** (1979). The distribution of tephra in the Papua New Guinea highlands. *Search* 10,228-230

PATON, T.R., HUMPHREYS, G.S. and **MITCHELL, P.B.** (1995). Soils: a new global view. University College London Press, London

PARFITT, R.L. and **MAVO, B.** (1975). Phosphate fixation in some Papua New Guinea soils. *Sci. New Guinea*, 3:179-190.

PICKUP, G. (1977) Computer simulation of the impact of the Wabo hydroelectric scheme on the sediment balance of the lower Purari. Purari river Hydroelectric Scheme Environmental Studies Vol 2. Office Envir & Conserv, and Dept Minerals & Ener (PNG)

PICKUP, G., HIGGINS, R.J. and **WARNER, R.F.** (1981). Erosion and sediment yield in Fly River drainage basins, Papua New Guinea. Symp. Eros. and Sedim. Trans. Pacific Rim Steeplands.IAHS Publ. 132

RADCLIFFE, D.J. (1983). Land Evaluation for Food Crop Production in Papua New Guinea. Paper presented at the 1st PNG Food and Nutrition Conference, Goroka. AFTSEMU Technical Report No. 2. (Mendi.). Republished as DPI Tech Report 85/8.

RADCLIFFE D.J. and **GILLMAN G.P.** (1985). Surface charge characteristics of volcanic ash soils from the Southern Highlands of Papua New Guinea. *Catena Suppl.* 7:35-46

REID, R.M. (1992). Cultural and medical perspectives on geophagia. *Medical Anthropology* 13:337-351

RICHARDS, P.W. (1941). Lowland tropical podsols and their vegetation. *Nature* 148,129-131

ROBBINS, R.G. (1960). The antropogenic grasslands of Papua and New Guinea. In: UNESCO symposium on the impact of man on humid tropics vegetation. Sept. 1960, Goroka, pp 313-329

RUTHERFORD, G.K. (1964a). Observations on the origin of a cutan in the yellow-brown soils of the highlands of New Guinea. In: A. Jongerius (ed) Soil Micromorphology. Elsevier, Amsterdam

RUTHERFORD, G.K. (1964b). The tropical soils of Mt Giluwe, Australian New Guinea. *Can. Geog.* 8,27-33

RUTHERFORD, G.K. and **WANTABE, Y.** (1966). On the clay mineralogy of two soil profiles of different age formed on volcanic ash in the Territory of Papua New Guinea. Proc. Int. Clay Conf., Israel. 1,209-219

RUXTON, B.P. (1967). Slopewash under mature primary rainforest in northern Papua. In: **J.N.** Jennings and J.A. Mabbutt (eds) Landform studies from Australia and New Guinea. ANU Press, Canberra

RUXTON, B.P. (1968). Rates of weathering of Quaternary volcanic ash in north-east Papua. Trans 9th Intern. Cong. Soil Science 4:367-376

RUXTON, B.P. And **MCDOUGALL, I.** (1967). Denudation rates in southeast Papua from patassium argon dating of lavas. *Amer. J. Sci.* 265,545-561

SCHROO, H. (1963). A study of highly phosphatic soils in a Karst region of the humid tropics. *Neth. J. Agric. Sci.*, 11:209-231

SCHROO, H. (1964). An inventory of soils and soil suitabilities in West Irian, IIB.. *Neth. J. Agric. Sci.*, 12:1-26.

SCOTT, R.M. (1965). Soils of the Port Moresby area. CSIRO Aust. Land Res. Ser. 14,129-145

SCOTT, R.M., HEALY, P.A. and **HUMPHREYS, G.S.** (1985). Land Units of Chimbu Province. CSIRO (Aust) Division of Water and Land Resources, Natural Resource Series no. 5. (CSIRO: Melbourne).

SILLITOE, P. (1993 a). Soil and cultivation in the Papua New Guinea highlands:II. a comparison of indigenous and scientific perspectives. *PNG J Agr. For. & Fish.* 36,1-21

SILLITOE, P. (1993 b). Losing ground? Soil loss and erosion in the highlands of papua New Guinea. *Land Degrad. & Rehab.* 4, 143-166

SIMONETT, D.S. (1967). Landslide distribution and earthquakes in the Bewani and Toricelli Mountains New Guinea. In: J.N. Jennings and J.A. Mabbutt (eds) Landform studies from Australia and New Guinea. Aust. Nat. Uni. Press, Canberra. pp 64-84

SOIL SURVEY STAFF (1975). Soil taxonomy: a basic system of soil classification for making and interpreting soil surveys. US Dept. Agric. Washington DC.

SOIL SURVEY STAFF (1992). Keys to soil taxonomy. 5th ed SMSS tech. monograph No. 19 Pocanhontas Press, Virginia.

SMYTHE, A.J. and **DUMANSKI, J.** (1993). FESLM: an international Framework for Evaluating Sustainable Land Management. World Soil Resources Report 73. FAO. Rome.

SPARLING, G.P. and **HUMPHREYS, G.S.** (1991). Changes in soil organic C and microbial biomass C after clearance of native forest for small-holder agriculture in Papua New Guinea, and for intensive pastoral agriculture in New Zealand. Dynamics of organic matter in relation to the sustainability of agricultural systems, Belgium 3-6 Nov. 1991.Extended abstract.

STANDAL, B.R. (1988). Possible role of acid soils in the etiology of the diseases Amyotrophic Lateral Sclerosis and Parkinsonism-Dimentia. In: J.L. Demeterio and B DeGuzman (eds) Proceedings 3rd International Soil Management Workshop on the Management and Utiliization of acid soils of Oceania. University of Guam. pp 254-261

TURVEY, N.D. (1974) Nutrient cycling under tropical rainforest in Central Papua. UPNG Dept Geography Occas. Paper. No 10

VENEMA, J.H. and **DAINK, F.** (1992). Papua New Guinea Land Evaluation Systems (PNGLES). AG:TCP/PNG/0152 Field Document No. 1. (Dept. Agriculture and Livestock (PNG) and Food and Agriculture Organisation).

WALLACE, K.B. (1973). Structural behaviour of residual soils of the continually wet highlands of Papua New Guinea. *Geotechnique* 2:203-218

WAYI, B.M. (1987). Development of a land suitability classification system for cocoa in Papua New Guinea. M.S. Thesis. (State University of Ghent: Belgium.)

WILLIAMS, A.R., FAIRCLOUGH, T.J. and **NIANFOP, M.P.** (1981). A report on the present soil erosion research programme of the Dept. Agriculture University of Papua New Guinea and suggestions for future work. Lowlands Landuse / Food Crops / Nutrition Research Meeting. Madang (mimeo)

WOOD, A.W. (1979). The effects of shifting cultivation on soil properties: an example from the Karimui and Bomai plateaux, Simbu Province, Papua New Guinea. *Papua New Guinea Agric. J.*, 30: 1-9.

WOOD, A.W. (1984). Land for tomorrow. Subsistence agriculture, soil fertility and economic stability in the New Guinea Highlands. Unpublished PhD thesis, University of Papua New Guinea

WOOD, A.W. (1985). The stability and permanence of Huli agriculture. Dept Geography Occas. Pap. No 5. UPNG

WOOD, A.W. (1987). The humic brown soils of the Papua New Guinea highlands: a reinterpretation. *Mountain Res. & Devel.* 7,145-56

WOOD, A.W. and **HUMPHREYS, G.S.** (1982). Traditional soil conservation in Papua New Guinea. In: L. Morauta, J. Pernetta and W. Heaney (eds) Traditional soil conservation in Papua New Guinea: Implications for today. Institute of Applied Social and Economic Research, PNG. pp 93-114

[i] Though this paper does not attempt to provide an historical account of the development of soil studies in PNG, it is pertinent to recall some of the early contributors who helped to lay the foundations for what followed. F.P. Aland, G.K. Graham, A.C. Hartley and P.G.E. Searle, who were Land Use Officers, are mentioned here as they have not been afforded the same recognition as achieved by the CSIRO soil scientists of P. Bleeker, H.A. Haantjens, G.K. Rutherford and R.M. Scott.

[ii] Within the Kuman speakers in Simbu the women, especially older women, appear to employ a very much more detailed terminology that is largely beyond the full comprehension of males. I became aware of this during soil investigations in 1979-81 but could not establish the full extent of this other than that there was another level beyond the common soil words such as magan kama (very good soil for cultivation).

[iii] There are about 150-200 PhD theses by anthropologist and geographers dealing with traditional agriculture in PNG and of these about a third contain considerable detail (R. Hide pers com).

[iv] An agrotechnology transfer workshop was held in PNG in 1983 (Anon 1983). Part of the widespread adoption of Soil Taxonomy in developing countries appears to stem from the policy of USAid to insist that this classification be used in agriculture based programs though, this did not occur in PNG.

[v] This soil type achieved a degree of infamy following the suggestion that it was the zonal soil (meaning that climatic influences overshadowed all others) of the humid tropical mountains (Haantjens and Rutherford 1964) when it was established that the parent material was the same *viz.* volcanic ash [See review by Wood (1987) and comment by Humphreys (1991).]

[vi] For example there is, as might be expected, considerable detailed information on chemical, physical, mineralogical and morphological properties of this soil especially those influencing plant growth (e.g Rutherford and Wantabe 1966; Parfitt and Mavo 1975; Bleeker 1983, Wood 1984; Humphreys 1984; Radcliffe and Gillman 1985; Moody & Radcliffe, 1986; D'Souza and Bourke 1986, Allbrook and Radcliffe 1987; Wood, 1987 and Kanua 1995). However, there are also studies on engineering properties (Wallace 1973; Blong & Pain 1978), pedogenesis (e.g. Haantjens and Rutherford 1964; Rutherford 1964a,b; Chartres *et al.* 1983; Chartres and Pain 1984) and soil loss on cultivated lands (Humphreys 1984, Wood 1984; Humphreys and Wayi 1991; Sillitoe 1993 b). Volcanic ash beds (or tephra), have also been used to unravel landscape evolution during the Quaternary at a regional scale (Pain and Blong 1979) and they provide useful marker beds in lacustrine, swampy and footslope deposits (e.g Blong and Pain 1976; Oldfield *et al.* 1980)

[vii] This was not the first attempt at establishing a major data base on soil and landscape data of PNG. Haantjens *et al.* (1975), Haantjens and Bleeker (1975) and Haantjens (1975) describe a computer data base system but it appears to have received little use. By the early 1980's it was impossible to retrieve any information from the data base - such was the rapid growth in computer software systems. In order to obtain soil information it was necessary to manually decode up to six fortran code sheets per soil profile which proved necessary in the land unit mapping exercise undertaken by Scott *et al.* (1985). The whole exercise can be best summed up as an expensive lesson.

[viii] Together with the more detailed surveys conducted by the Land Use Section and affiliates, about half of PNG has been mapped.

[ix] There appears to be little firm evidence to go on but it might be surmised that some information on erosion was known, though not directly quoted. Brune (1949) considered that about 75% of erosion was due to sheet wash in some coastal areas of PNG but that because of high vegetation cover total soil loss amounted to < 2 tonnes ha^{-1} y^{-1} for catchments < 270 km^2. However, it was also known that considerable sediment loads were produced by large catchments. Fournier (1960) used a limited but widespread data set to predict global rates of denudation based on an index that emphasises seasonality. A small scale map indicated a denudation rate of 10-20 t ha^{-1} y^{-1} over PNG. An update using a more complete rainfall data would imply rates between about 10 and 100 t ha^{-1} y^{-1} with a country wide average of about 23 t ha^{-1} y^{-1}.

[x] According to FAO (1978) <10 t ha^{-1} y^{-1} amounts to slight erosion, 10-50 is moderate, 50-200 is high and >200 t ha^{-1} y^{-1} is very high.

[xi] op cit (iii)

[xii] The study showed that the rate of nutrient decline varied between soil types in an expected and predictable way. The beauty of the study is in dating the gardens and establishing the history of each sampled garden plot which was possible by the very detailed oral records retained by the local farmers. The oral history was subsequently confirmed by Chris Ballard (pers com) who has cross checked fifteen generations of information across several Huli sub-clans and independently confirmed key events by utilising dated archaeological sites. See also Wood (1985) for a summary and Blaikie and Brookfield (1987) for an even briefer treatment.

[xiii] The extent of Tibito tephra, as shown in Figure 5, is fairly well dated and mapped (Blong 1982; Pain and Blong 1979). The possible extent of ash fall during the Holocene is based on the position of volcanic centres that have been active in historical times together with seasonal wind patterns. However, the distribution pattern of Tibito Tephra and an older ash fall, Olgaboli Tephra, do not conform with major seasonal wind directions which implies that the extent of ash is somewhat greater than mapped here.

[xiv] During 1997, PNG experienced the biggest drought in living memory and possibly greater than any thing in the last 120 years or more (Allen and Bourke 1997). It is now well known that these droughts are a part of the periodic El Nino - Southern Oscillation (ENSO) phenomenon.

[xv] There is no indication in Humbert's paper as to how much time was spent in the field in PNG for this study nor of any other areas that may have been visited. Furthermore, I know of no other paper by this author on PNG soils. It is possible that he/she was with the armed forces, presumably American, during the Pacific campaign of WWII. For example, Brune (1949) records that his observations on soils and erosion in the SW Pacfic were made during WWII.

[xvi] Climatic determinism still dominates pedological thinking today. Soil Taxonomy (an influential soil classification system) retains a very strong implicit link to climatic determinism. Yet the questionable utility in calling a soil a tropical soil in a tropical settings (e.g. tropepts) does not appear to have registered. See Haantjens and Bleeker (1975) and Humphreys (1991) for further comment.

INTERPRETING SOIL DATA FROM THE PAPUA NEW GUINEA RESOURCE INFORMATION SYSTEM (PNGRIS)

David F. Freyne

ABSTRACT

The Papua New Guinea Resource Information System (PNGRIS) is an inventory of natural resources, land use and population distribution. At a scale of 1:500,000 it is the most comprehensive assembly of information on PNG soils and their distribution. PNGRIS is an easily accessible source of soil data at a level suitable for national and provincial planning. In this paper, examples are given how the soil data can be used illustrating the value of this computerized database with its linked mapping capability.

***Keywords:** soil information, digitized data, soil mapping, PNGRIS, Papua New Guinea.*

INTRODUCTION

The Papua New Guinea Resource Information System (PNGRIS) is a computer based inventory of information on natural resources, land use and population distribution which covers the whole nation (Bellamy and McAlpine 1995). It was designed to be a basic tool in resource use planning for both development and conservation. It is now installed and used in a wide range of PNG agencies involved in service provision and natural resource based activities

PNGRIS was established as a cooperative research project undertaken and funded jointly by the PNG Department of Primary Industry (DPI, now Department of Agriculture and Livestock (DAL)) and CSIRO. The project's objective was to determine both the current use and development potential of the nation's natural resources for food and cash production, taking into account present and future population growth and distribution. The aim was to integrate information relevant to development planning and to provide a system for effective use and evaluation of that information.

All of the information in PNGRIS was derived from natural resource surveys previously undertaken by DPI and CSIRO, geology mapping carried out by the Geological Survey of PNG and the Australian Bureau of Mineral Resources and population data and smallholder economic activity compiled by the National Statistics Office with data collected from the 1980 and 1990 censuses. The broad structure of PNGRIS is shown in Figure 1.

THE STRUCTURE OF PNGRIS

PNGRIS consists of: (1) a map base (in MAPINFO) showing the locations of the basic spatial units of the system known as Resource Mapping Units (RMU) and, (2) a database (in FOXPRO) comprising the inventory data describing the natural resource, land use and population distribution of each RMU. These are linked by a user-friendly interface for joint map and database analysis. The basic unit of information used to integrate and store data in PNGRIS is the *Resource Mapping Unit* (RMU). An RMU is an area of land that has the same pattern of landform, geology, climate, hydrology and soils throughout its extent. In the sense that it is made up solely of physical resource attributes it is effectively time independent (i.e. unlikely to change except over the long term). For each RMU, information is recorded on its natural (physical) resources to which is added further information on land use, population and natural (biological) resources, all of which are time dependent (i.e. likely to change over the short to medium term). The concept of an RMU is largely similar to the *land system* concept defined by Christian and Stewart (1968) and used by CSIRO as the mapping unit for its large-scale regional survey program (see definition later

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Figure 1. **PNGRIS Components.**

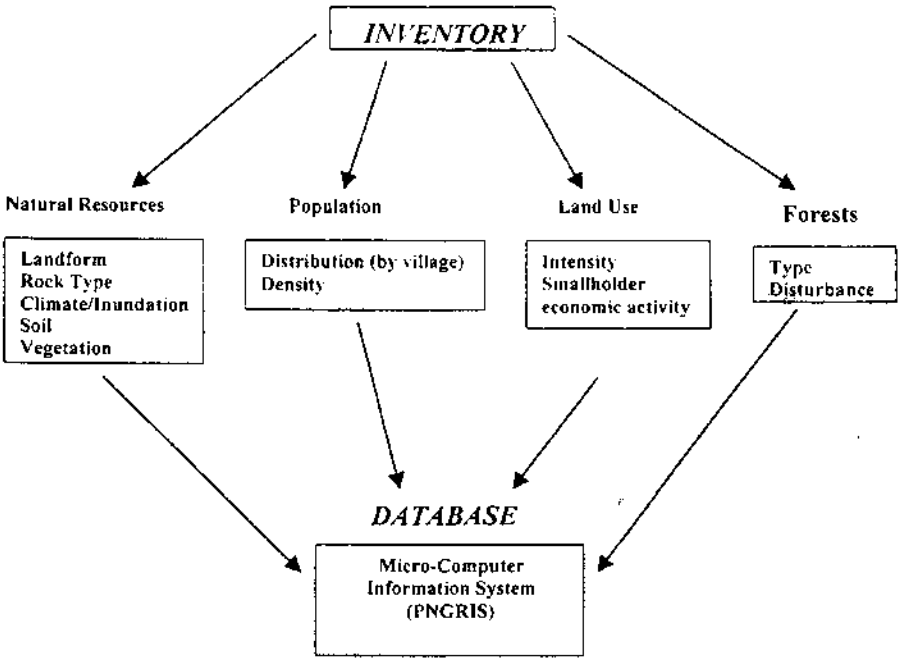
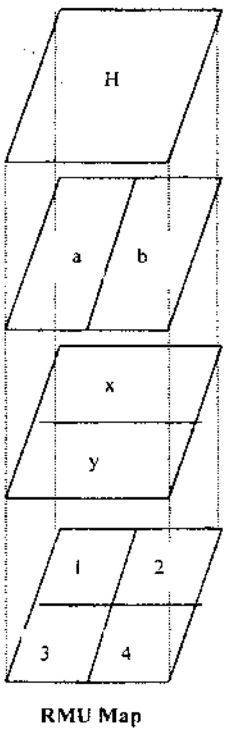


Figure 2. **Example of the derivation of an RMU map (after Bellamy and McAlpine 1995).**



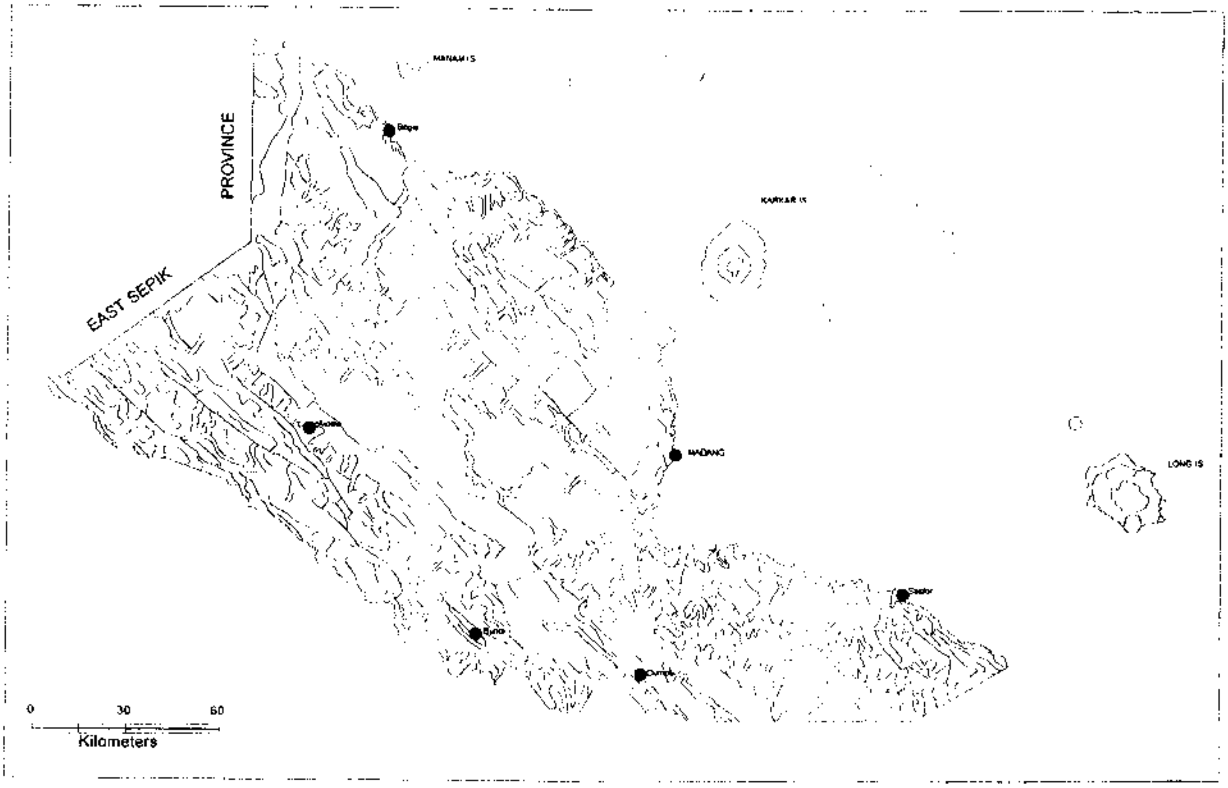
Attribute I: Landform type
H - hills

Attribute II: Rock type
a – ultrabasics
b – fine grained matamorphics

Attribute III: Altitude
x – 1200 to 1800 m
y – 1800 to 2100 m

RMU No.	Attributes			Description
	I	II	III	
1	H	a	x	Hills on ultrabasics between 1200 & 1800 m
2	H	b	y	Hills on fine grained metamorphics between 1200 & 1800 m
3	H	a	x	Hills on ultrabasics bewteen 1800 & 2100 m
4	H	b	y	Hills on fine grained metamorphics between 1800 & 212100 m

Figure 3. **Example of RMU mapping for Madang Province.**



in this paper). The total attribute set used to describe RMUs is given in Table 1. RMUs were derived by overlaying mapped attribute data to generate boundaries. Thematic maps of three attributes, namely landform type, rock type and altitude, were used to define the basic RMU as shown in Figure 2. An example of RMU mapping is given in Figure 3 and a description for one RMU is given in Table 1.

Map compilation and information integration has been carried out at a scale of 1:500,000 with 4566 RMUs having been delineated for the country as a whole. Maps have been digitised into computer compatible form, on a province by province basis, with whole country mapping also being available.

A detailed description of the computer implementation aspects of PNGRIS is provided in the *PNGRIS User's Guide* compiled by Keig and Quigley (1995). The system has been designed as an integrated database and consequently caution should be taken in desegregating the data for specific attribute analysis.

DATA SOURCES USED FOR PNGRIS

CSIRO

As mentioned before, a large amount of knowledge describing resource type and distribution, built up by CSIRO and various PNG Departments over a long period, was used as the basic source material for the PNGRIS inventory. The principal sources of natural resource information were the regional resource surveys undertaken by the CSIRO Division of Land Research, Canberra between 1953 and 1972 and subsequent disciplinary studies of the whole country. These regional resource or 'land system' surveys were designed to provide rapid information on the natural resources of large areas of PNG, both in inventory and map form, for the initial assessment of agricultural potential and limitations. The surveys involved close integration of specialist studies (namely, landform, soil, climate and vegetation), extensive use of aerial photographs, reconnaissance ground sampling and multi-attribute land classification.

Table 1. Example of PNGRIS information in an RMU.

PROVINCE 13 Madang
DISTRICT 2 Madang

RMU No. 1

LAT 5 deg 7 min S
LONG 145 deg 47 min
AREA 99 sq km

NATURAL RESOURCES

LANDFORM Raised coral reefs and associated back reef plains

ROCK TYPE Alluvial deposits
Limestone

SLOPE <2 degrees

ALTITUDE 0-600 m
MAX TEMP 32-30 degC
MIN TEMP 23-19 degC

RELIEF Negligible <10 m

RAINFALL

Annual	3500-4000 mm
Seasonality	100-200 mm to >200 mm
Deficit	Infrequent, slight deficit

INUNDATION Waterlogged area
Extent <20%

VEGETATION See Land Use file

FOREST TYPE

	sq km
Hm - Low alt on uplands - medium crowned forest 50% undisturbed	9

LAND USE

'USED' AREA 91 sq km = 92 % of total area

POPULATION DENSITY

Total Population	34103	
Density on Total Area	344	persons/sq km
Density on 'Used' Area	375	persons/sq km

LAND USE INTENSITY

	sq km
Significant	90
Low	1

REGROWTH

No fallow (i.e. totally used)	46
Mixture of tall and short woody	44
Tall woody	1

NON-SUBSISTENCE USE

Coconuts w/wo under-cropping
Urban

SMALLHOLDER ECONOMIC ACTIVITY

Total Households 5353

	Households			Households	
Activity	No	% Total	Activity	No	% Total
cocoa	172	3	spices	28	1
coffee	18	0	fish	245	6
rubber	0	0	grow others	8	0
oil palm	0	0	pigs	208	8
c'nut/copra	375	10	poultry	90	8
betelnut	481	14	goats	0	0
fruit	352	12	cattle	1	0
banana	410	16	sheep	0	0
veg crop	419	15	raise others	1	1

SOILS

SOIL 1 Tropofluvents
Mainly well drained undifferentiated soils with high (>=0.2%) or fluctuating org C to >=125cm

EXTENT	30-50% of RMU	ERODIBILITY	Moderate
DEPTH	Deep (>1m)	REACTION	Weakly acid to
DRAINAGE	Well-drained	AVAIL WATER CAPACITY	
STONINESS	Not stony/rocky (<1%)	0-25 cm	Low
SALINITY	None	0-50 cm	Moderate
CATION EXCH	High (>25 meq%)	0-100 cm	High
BASE SAT'N	High (>60%)	MIN RESERVE	High
% NITROGEN	Moderate (0.2-0.5%)	TEXTURE TOP	Medium
AVAIL P	High (>20ppm)	TEXTURE SUB	Medium
EXCHK	Moderate (0.2-0.6 meq%)	ANION FIX'N	No problem

SOIL 2 Fluvaquents
Poorly drained, undifferentiated soils with high (>=0.2%) or variable org C contents to >=125 cm

EXTENT	20-40% of RMU	ERODIBILITY	Moderate
DEPTH	Deep (>1m)	REACTION	Weakly acid to
DRAINAGE	Poorly to very poorly	AVAIL WATER CAPACITY	
STONINESS	Not stony/rocky (<1%)	0-25 cm	Low
SALINITY	None	0-50 cm	Moderate
CATION EXCH	High (>25 meq%)	0-100 cm	High
BASE SAT'N.	High (>60%)	MIN RESERVE	High
% NITROGEN	Moderate (0.2-0.5%)	TEXTURE TOP	Very fine
AVAIL P	High (>20ppm)	TEXTURE SUB	Very fine
EXCHK	High (>0.6 meq%)	ANION FIX'N	No problem

SOIL 3 Rendolls
Shallow, dark, weakly acid to neutral soils formed on calcareous parent materials

EXTENT	20-40% of RMU	ERODIBILITY	Low
DEPTH	Very shallow (<25cm)	REACTION	Weakly acid to
DRAINAGE	Well-drained	AVAIL WATER CAPACITY	
STONINESS	Moderately stony/rocky	0-25 cm	Very low
SALINITY	None	0-50 cm	Very low
CATION EXCH	High (>25 meq%)	0-100 cm	Very low
BASE SAT'N	High (>60%)	MIN RESERVE	High
% NITROGEN	High (>0.5%)	TEXTURE TOP	Medium
AVAIL P	High (>20ppm)	TEXTURE SUB	Medium
EXCHK	Moderate (0.2-0.6 meq%)	ANION FIX'N	No problem

SUSTAINABILITY

	SOIL 1 (30-50%)	SOIL 2 (20-40%)	SOIL 3 (20-40%)
CHEMICAL FERTILITY	High	Very High	Very High
INHERENT FERTILITY	Very High	Very High	Moderate
SOIL ERODIBILITY	Moderate	Moderate	Low

SOIL FORMATION	Moderate (1.2mm - 1.6mm / year)
RAINFALL EROSIVITY	High (30,001 - 40 000 Joules sq. m)
INUNDATION / SLOPE	Little inundation
TECTONICITY	Areas subject to common earthquakes of low magnitude
MASS MOVEMENT	Nil

RURAL POPULATION AND VILLAGES (1990)

	Total Population
1980	27216
1990	34103

District	Division / Village	Population
Dist 2 Madang	Divsn 9 North Ambenob	
	Village 7 BUOAD	168
	Village 22 MALAMAL	323
	Village 25 MIS	517
	Village 29 RIWO	516
	Village 31 SEK	810
	Village 32 SIAR	904
	Village 33 SILIBOB	275
	Village 501 ALEXISHAFEN CTH	80
	Village 502 AMRON LUTH MISS	169
	Village 503 BAITABAG LUTH	200
	Village 508 MILILAT PLTN	311
	Village 509 NAGADA	394
	Village 510 ST FIDELIS COLL	377
	Village 511 SIAR PLTN	152
	Village 512 VUDAR PLTN	43
Dist 2 Madang	Divsn 13 Sek - Rempi	
	Village 4 BAGILDIK	240
	Village 7 BOMASA	472
	Village 8 DEDA	257
	Village 9 KAWE	222
	Village 11 SEMPI	236
	Village 501 MURUNASS PLTN	127
	Village 502 WEWAK TIMBERS	203
Dist 2 Madang	Divsn 14 Saker - Garus	
	Village 12 KUDAS	114
	Village 15 MATUKAR	228
	Village 501 MATUKAR PLTN	128

A basic assumption of the land system surveys was that the landscape is organized in an hierarchical structure, such that small relatively uniform land components (land units) are arranged in larger spatially contiguous but recurrent patterns to form complexes (land systems) (Christian and Stewart 1968; Mabbutt 1968). Information is provided at two levels of spatial resolution: descriptive information at *land unit* level, and mapped information at *land system* level. A land unit is defined as a group of similar sites that can be described in terms of major inherent characteristics of consequence to land use. A land system is defined as an assembly of land units which are geographically and/or geomorphologically related, and throughout which there is a recurring pattern of landform, soils, and vegetation (Christian and Stewart 1968).

Landform, and particularly geomorphology, was the basic factor used in defining and delineating both the land system and its subsidiary components (land units). The methodology depends on the assumption that visible differences in landform and geomorphology (as recognized on aerial photographs) will reflect, in general, differences in the associated resources (such as soils, vegetation and climate).The regional resource survey program collected and presented information in an 'integrated' form. It did not provide resource information for presentation on an individual disciplinary basis.

After the conclusion of the regional resource survey program a series of publications were prepared which drew together existing information either as compendia (Analytical Soils Data for PNG, Bleeker and Healy 1980; Climatic Tables for PNG, McAlpine *et al.* 1975), or as maps at a scale of 1:1,000,000, indicating the type and distribution of a resource (Geomorphology Map of PNG, Loffler 1974; Vegetation Map of PNG, Paijmans 1975). The latter two maps were based on extrapolation of the previous regional survey data using air photography, with small gaps filled in with SLAR. Finally, four definitive reference books were produced covering the vegetation (Paijmans 1976), geomorphology (Loffler 1977), soils (Bleeker 1983) and climate (McAlpine *et al.* 1983) of PNG.

Other Data

The information described above was combined with information from four other sources:

* Reconnaissance, semi-detailed and detailed soil and land resource surveys carried out by the Department of Primary Industry over a period of forty years. These surveys covered complete provinces (Simbu, New Ireland and Manus), large regional areas (Talasea-Bialla Area of West New Britain, Markham Valley of Morobe Province, Abau District of Central Province and many others) plus hundreds of localized project areas.

* PNG 1:250 000 Geological Series maps covering the whole of the country and published by the Bureau of Mineral Resources, Geology and Geophysics, Department of National Development Australia and the Geological Survey of Papua New Guinea, Department of Minerals and Energy, Papua New Guinea.

* 1:100 000 Topographic Survey maps covering the whole of the country and available from the National Mapping Bureau, Department of Lands and Survey, Papua New Guinea.

* National censuses of population and agricultural activity in 1980 and 1990

PNGRIS SOILS DATA

Provision of information about soil attributes, for the country as a whole, based on limited soil data acquired through reconnaissance surveys, presented a major problem of spatial extrapolation. It was necessary to derive soils data on the basis of observed correlations between soil characteristics and landforms and vegetation as seen on aerial photographs. Certain levels of generalization in soil classification and in attribute description are, therefore, essential to allow spatial extrapolation with a reasonable degree of confidence in its reliability.

It is important to understand that soil types were determined within the boundary of each RMU (see Figure 2), either from existing data on the RMU or by extrapolation, and that the only additional soil boundaries that can be defined using PNGRIS will be derived from amalgamation of adjoining RMUs. The soil classification adopted for the inventory is the USDA scheme of Soil Taxonomy (U.S. Dept of Agriculture 1975). This system is internationally accepted and has been used in PNG since the DPI

Table 2. **Great soil groups within the order Entisols, their distribution and correlation to previously named soil groups.**

Order	Sub-Order	Great Group	Distribution	Major previously named soil group
Entisols	Aquents	Cryaquents	Very local	Skeletal soils, Peat soils.
		Sulfaquents	Common	Saline Peats and Muds, Mangrove soils
		Hydraquents	Very common	Young Alluvial soils. Very poorly drained Alluvial soils
		Fluvaquents	Very common	Alluvial soils, Young Alluvial soils, Recent Alluvial soils
		Tropaquents	Very common	As for Fluvaquents
		Psammaquents	Common	Recent Alluvial soils
	Psamments	Tropopsamments	Common	Coarse textured Beach soils
		Ustipsamments	Very local	Coarse textured Beach soils
	Fluvents	Tropofluvents	Common	Young Alluvial soils, Recent Alluvial soils, Coarse textured Beach soils
		Ustifluvents	Local	As for Tropofluvents
	Orthents	Troporthents	Very common	Lithosols, Skeletal soils, Slope soils
		Cryorthents	Very local	As for Troporthents
		Ustorthents	Very local	Colluvial soils

study undertaken in the Markham Valley (Holloway *et al.* 1973). Also Bleeker (1983) used Soil Taxonomy to classify PNG soils for his book on the subject.

Data Sources

The principal sources of information for the classification of soil class in each Resource Mapping Unit were:

* Analytical Data on PNG soils (Bleeker and Healy 1980)
* Soils of PNG (Bleeker 1983)
* CSIRO Land Research Series publications (1964-76)
* DPI and DAL Publications and unpublished soil survey

At the outset the Great Soil Groups tentatively identified in PNG were correlated with previously named soils groups (as identified in the CSIRO Land Research Series (1964-1976) and DPI) and an estimate made of the distribution of each. These are listed in the PNGRIS Handbook (Bellamy and McAlpine 1995) and an example for one Soil Order shown in Table 2.

In view of the broad scale of mapping (1:500,000), the limited amount of available soil information and the need to keep the resource attribute descriptions to a manageable size, a maximum of three different soils were listed for each RMU. As a general rule 'minor' soils assessed to cover less than 20% of the RMU are not listed. When only one soil is described in the RMU it covers by definition more than 80% of the total area. RMUs with two soils were considered to cover an approximate area of 40 to 60% for the first, and 20 to 40% for the second great soil group. If three soils are listed in RMU description, the areal distribution will be 30-50% for the first and 20-40% for the second and third great soil groups.

Soil Attributes

Soil attributes used as criteria to distinguish 'great soil group' classes (Soil Taxonomy, USDA 1975) are often inadequate by themselves for meaningful land evaluation for agricultural uses. Consequently, for each great soil group described in an RMU, an additional data set of 15 soil attributes is provided. These soil attributes are listed in Table 2 and are grouped into physical and chemical properties. This additional soil information is required for matching crop requirements to land characteristics for land evaluation. It also provides soil information at a level more readily understood by users not familiar with the terminology used Soil Taxonomy.

These soil attributes were derived primarily from the compendium of Analytical Data of PNG Soils (Bleeker and Healy 1980) and soil analytical data contained in the files of the Land Utilization Section of the Department of Agriculture and Livestock, Port Moresby. Where available, soil attribute descriptors for each RMU are derived directly from the sources referred to above. For those RMUs without field observation or analytical data, the soil attribute descriptors were derived, using the database, through extrapolation of soil data from other RMUs with similar environment characteristics (such as climate, rock type, landform, vegetation) and modified by field experience. To facilitate spatial extrapolation, as well as data storage, the values for each attributes were classified, and class codes are used in the database as attribute descriptors. It was recognized that this extrapolation may be subject or errors, therefore the system was established to enable corrections to the database to be made whenever site specific information becomes available.

USING THE SOILS INFORMATION IN PNGRIS

In the introduction to the 2nd Edition of the PNGRIS Handbook, Bellamy and McAlpine remind users that the system was designed as an integrated database and caution against desegregating the data for specific attribute analysis. Nevertheless, soil workers with in-depth experience of Papua New Guinea environments have demonstrated that the soils files in PNGRIS provide a most valuable and convenient source of data to evaluate land use potential and soil management strategies at provincial and national level. The following four applications of PNGRIS demonstrate how the system may be used for a variety of applications.

Extent of acid soils

Humphreys and Freyne (1987) used the RMU mapping aspect of PNGRIS to estimate the extent of acid soils in Papua New Guinea. At the time of compiling the soil database for PNGRIS, there was a widespread interest in acid soils in tropical regions, which prompted the building-in of the capacity to identify their occurrence and distribution. Soils with pH < 5.5 were assumed to have aluminium toxicity problems. For their assessment Humphreys and Freyne defined "potential acid soils" as those with:

(i) pH (1:1 water) < 5.5
(ii) effective CEC < 5 cmol/kg (≈CEC <cmol/kg)
(iii) belong to the orders Oxisols or Ultisols or Inceptisols (but excluding Andepts)
(iv) are the dominant or co-dominant soil of an RMU

Based on this definition it was possible to use PNGRIS to map the distribution of potential acid soils in PNG. According to PNGRIS these soils occur in eleven (11) out of the nineteen (19) provinces, cover some 52,049 km^2 or 11.3% of the country and in 1980 supported 2.5% of the population. They are confined to coastal provinces and are found at altitudes <1,000 m a.s.l. with rainfall between 1,500 and 3,000 mm per annum.

Using PNGRIS it was possible to assess the intensity of the utilization of acid soils for both subsistence agriculture and cash crop production. It is notable that in 1980, while less than 15% of acid soils were being used and at a very low level of intensity, they are being used to produce coconuts, coffee and spices. Humphreys and Freyne demonstrated that PNGRIS provides a reliable source of data for mapping the occurrence and intensity of use of broadly defined soil types at a national level.

Land evaluation for arabica coffee

Harding, Bleeker and Freyne (1987) used PNGRIS mapping functions and soils data to compile a series of maps and accompanying report on the potential for arabica coffee production in Western Highlands Province. The following brief description of the mapping procedure followed by Harding and Freyne (1987).

At the outset, altitude Land Mapping Units (LMUs) were defined by modifying the contours provided on the 1:250,000 topographic maps. These were then subdivided with slope-steepness categories derived from the relevant 1:100,000 and 1:250,000 scale topographic maps and further divided by the appropriate rainfall isohets. The resultant LMUs were overlain with PNGRIS soil data to provide information on drainage/effective soil depth, erosion hazard and chemical fertility to generate a 1:250,000 scale map showing Suitability Mapping Units (SMUs). The reader is referred to the detailed description of the systematic procedures followed provided in the report.

Provincial Atlases

A series of three Provincial Resource Atlases were produced by a CSIRO team to undertake the upgrading of PNGRIS, and addition of a mapping capacity, from its original KMAN format to FOXPRO and MAPINFO. These atlases, one each for Madang, Morobe and Eastern Highlands Provinces, provide data on population distribution in 1990 in respect to generalized maps of the natural resources, including soil distribution. The maps are presented at 1:1,000,000 scale and are suitable for providing an indication of development potential only. Site specific investigations should be undertaken to confirm any potential indicated by the maps.

Mapped at 1:1,000,000 scale the soils information has been aggregated to the Order level thus making PNGRIS an ideal source of information. It would be possible to compile provincial soil maps at 1:500,000 scale using the PNGRIS soils files as the source information describing the soil classes at great group level.

These atlases provide and ideal source of information for educational purposes and should be available for all schools within each province. In addition, while the level of detail provided is not sufficiently detailed for planning, they serve to make planners and developers aware of the types of information and spatial relationships which should be considered in the decision making process.

Soil map of PNG

Bleeker (1988) used PNGRIS as the primary source of data in compiling the Soil Map of Papua New Guinea. As a first step data provided for each of the 4562 RMUs in PNGRIS "were grouped into approximately 600 classes, each having a similar suite of soils. The second stage involved the amalgamation of these 600 classes in more generalized assemblages of soils called soil associations." This resulted in a total of seventy-two soil associations. These associations were then combined into twenty-two more generalized major groupings, which have similar characteristics and are colour coded on the map.

In addition to providing the basic source of data for the soil map Bleeker used PNGRIS files to relate the soil associations to several other land attributes important for land evaluation, namely slope, texture and phase of the dominant soil. Four (4) slope categories, five (5) texture classes and five (5) soil phases were used in compiling the final map, all interpreted from the PNGRIS database. Finally, having mapped the soil associations using PNGRIS it was then possible to utilize the database to calculate the area within each class on a provincial basis or for the country as a whole.

CONCLUSION

PNGRIS soils data provides an ideal source of information for a wide variety of applications. It requires careful interpretation, is well suited to national and provincial level planning but should not be used at project level.

REFERENCES

BELLAMY, J.A. and **McALPINE, J.R.** (1995). *Papua New Guinea Inventory of Natural Resources, Population Distribution and Land Use Handbook*, 2nd Ed. PNGRIS Publication No. 6 (AusAID: Canberra)

BLEEKER, P. and **HEALY, P.A.** (1980). *Analytical data of Papua New Guinea Soils*. CSIRO , Division of Land Use Research, Technical Paper No. 40, Vols. 1 & 2.

BLEEKER, P., (1983). *Soils of Papua New Guinea*. CSIRO and ANU Press, Canberra.

BLEEKER, P., (1988). *Explanatory notes to the soil map of Papua New Guinea*. CSIRO, Division of Water Resources, Natural Resources Series No. 10.

CHRISTIAN, C.S., and **STEWART, G.A.** (1968). *Methodology of integrated surveys*. In 'Aerial Surveys and Integrated Studies. Proceedings of Toulouse Conference 1964', pp 233-80. (UNESCO : Paris).

HARDING, P.E., BLEEKER, P. and **FREYNE, D.F.** (1987). *Land Suitability Evaluation for Rainfed Arabica Coffee Production: Western Highlands Province, Papua New Guinea*. Coffee Research Report No. 4. C.R.I., Kainantu.

HOLLOWAY, R.C., ZIJSVELT, M.F.W., KNIGHT, M.J., BRIGATTI, J.M., LEGGER, D., STRONG, B.W., ALAND, F.P., BLACKBURN, K.J. and **HOLTZKNECHT, H.A.** (1973). *Land Resources and Agricultural Potential of the Markham Valley*. Res. Bull. No. 14, Dept. of Agric., Stock and Fish., Port Moresby.

HUMPHREYS, G.S. and **FREYNE, D.F.** (1987). *Acid soils in Papua New Guinea*. 3rd International Management Workshop entitled "Management and Utilisation of Acid Soils of Oceania", Palau, 2-6 February 1987.

KEIG, G. and QUIGLEY, J.B. (1995). *PNGRIS User's Guide*. Prepared by CSIRO for AusAID

LÖFFLER, E. (1974) *Explanatory notes to the Geomorphology Map of Papua New Guinea*. CSIRO Aust., Div. Land Use Res., LRS No. 33

LÖFFLER, E. (1977) *Geomorphology of Papua New Guinea*. CSIRO and ANU Press, Canberra.

MABBUTT, J.A. (1968). *Review of concepts of land evaluation In 'Land Evaluation'*. ed. G.A. Stewart, pp 11-29. Macmillan, Australia.

McALPINE, J.R. GAEL KEIG and KAREN SHORT, (1975) *Climatic Tables for Papua New Guinea*. Tech Paper N0. 37. Div. of Land Use Research, CSIRO, Australia.

McALPINE, J.R., KEIG, G. with FALLS, R. (1983). *Climate of Papua New Guinea*. CSIRO and ANU Press, Canberra.

PAIJMANS, K. (1975) *Explanatory notes to the vegetation map of Papua New Guinea*. CSIRO Aust. Land Res. Series No. 36

PAIJMANS, K. ed., (1976). *New Guinea Vegetation*. CSIRO and ANU press, Canberra.

SAVAGE, T.J., QUIGLEY, J.B. TRANGMAR, B.B. and McALPINE, J.R., (1995). *Resource Atlas of Eastern Highlands Province, Papua New Guinea*. Prepared by Landcare Research New Zealand Ltd and CSIRO for AusAID, Canberra

SAVAGE, T.J., QUIGLEY, J.B., TRANGMAR, B.B. and McALPINE, J.R. (1995). *Resource Atlas of Madang Province, Papua New Guinea*. Prepared by Landcare Research New Zealand Ltd and CSIRO for AusAID, Canberra

SAVAGE, T.J., QUIGLEY, J.B., TRANGMAR, B.B. and McALPINE, J.R. (1995). *Resource Atlas of Morobe Province. Papua New Guinea*. Prepared by Landcare Research New Zealand Ltd and CSIRO for AusAID, Canberra.

UNITED STATES DEPARTMENT OF AGRICULTURE (1975). *Soil Taxonomy: a Basic System of Soil Classification for making and interpreting soil surveys*. US Govt. Printer, Washington, D.C.

PROPERTIES AND MANAGEMENT OF ANDISOLS IN THE HIGHLANDS OF PAPUA NEW GUINEA

David J. Radcliffe[1] and Mathew B. Kanua[2]

Abstract

*Andisols occupy 5.5% of land in Papua New Guinea. The Andisols in the central and western highlands are derived mainly from Quaternary tephras and support semi-permanent agricultural systems based on sweet potato (*Ipomoea batatas *L.). The parent material, and the humid conditions under which pedogenesis has occurred, has given rise to a particular set of physical and chemical properties which determine how these soils are presently managed and how their management may be improved. Analysis of a range of benchmark Andisols showed low bulk density, high moisture retention, a significant proportion of variable charge associated with the exchange complex, and a very high capacity for phosphorus sorption. Soil chemical fertility is the main constraint to crop production. Inferences are drawn from literature review and previous experimentation on increasing the nutrient supply including partial quenching of the P sorption capacity, correction of potassium and micronutrient deficiencies through the use of both organic and inorganic fertilizers, and raising the base status and cation exchange capacity. Recommendations are made for future research within a farming systems perspective.*

Keywords: *Andisol, Allophane, tropical highlands, phosphorus sorption, soil management, variable charge soils, volcanic ash soils, Papua New Guinea.*

INTRODUCTION

Andisols are soils developed in volcanic ash or other pyroclastic materials. Papua New Guinea (PNG) is the site of considerable volcanic activity, and there is evidence of extensive eruptions during the Pleistocene period. Andisols are therefore common in PNG and occupy about 5.5% of the country's total land mass. The distribution of Andisols is shown in Figure 1. They are the dominant cultivated soils in the central and western highland provinces, where semi-permanent agricultural systems based mainly on sweet potato (*Ipomea batatas* L.) support some of the highest rural population densities in the country. Andisols also occur in the lowlands, especially in the islands and atolls, where they are developed in more recent tephras and often have a high proportion of volcanic glass. The lowland Andisols have a somewhat different set of properties, and are generally less intensively cultivated than those in the highlands. The estimated distribution of volcanic landforms, which are expected to be dominantly overlain by Andisols, with their human population is given in Table 1. More than 15% of the human population, and an undisclosed livestock population subsist on Andisols in PNG. The origin of Andisols from unconsolidated volcanic materials gives rise to particular physical and chemical properties which influence the way in which they are managed under traditional systems and determine their potential for improved management. In spite of the uniqueness of such properties and the importance of this soil group in the highland rural economy, relatively little research into their management has been carried out. Much of this research has been conducted under rural development projects with specific areal coverage and limited life spans, which has led to a fragmented approach and prevented the development of a systematic research programme. Furthermore, the specificity of environmental and socio-economic conditions in the PNG highlands limits

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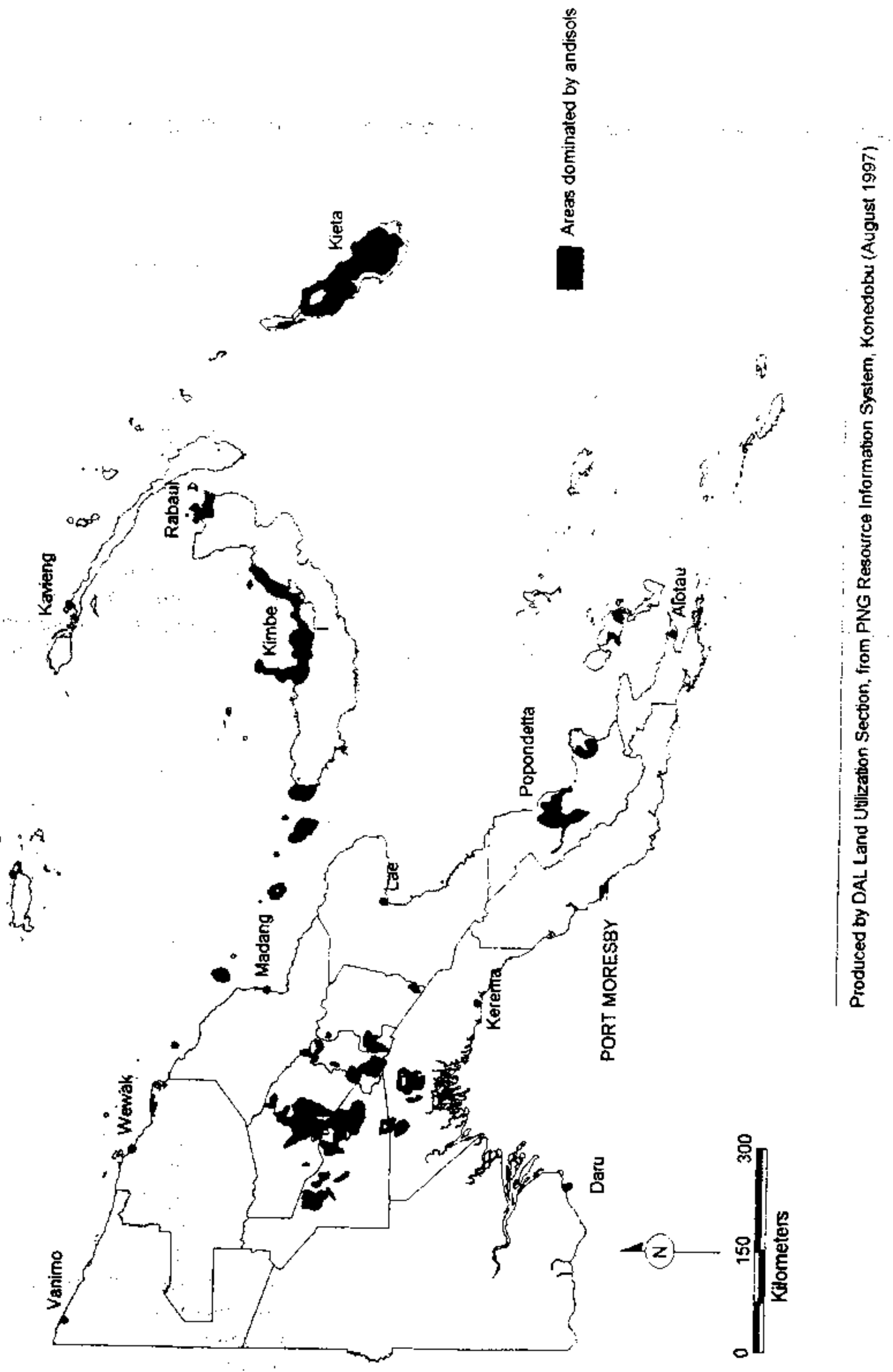


Figure 1. Distribution of Andisols in Papua New Guinea.

Table 1. **Distribution of Volcanic Landforms and their associated Population Distribution in Papua New Guinea.**

Province	Area	Population		Agricultural land use (km²)	
	(km2)	1980	1990	1975	1996
Gulf	1170	0	0	37	37
Milne Bay	431	7311	8723	298	304
Northern	2294	24230	30424	856	1008
Southern Highlands	3619	98263	130739	2187	2221
Enga	618	46791	62608	376	376
Western Highlands	2186	109529	126067	1463	1492
Simbu	1445	18263	22022	434	474
Eastern Highlands	427	1528	1474	60	60
Morobe	894	6770	8853	292	96
Madang	881	30650	36302	375	375
East Sepik	50	2127	2439	47	47
East New Britain	860	68815	99014	693	701
West New Britain	4664	58078	87348	1185	1375
North Solomons	5869	84916	84916	3916	3916
Total	**25408**	**557271**	**700929**	**12219**	**12682**

the transfer of research experience on Andisols in other countries. This paper reviews research on the properties of the highland Andisols of PNG, with particular reference to their management under traditional and improved agricultural systems.

GENESIS AND CLASSIFICATION

Highland Andisols are derived mainly from volcanic ash, or tephras which originate from eruptions which occurred more than 50,000 years ago in the Pleistocene epoch (Blong and Pain 1978). The depth of tephra accumulated is determined by amount extruded and its properties, the distance from the source, the direction of the prevailing wind, and the nature of the landforms on which it is deposited. Total depths of 20 m have been reported on the slopes of Mount Giluwe (Pain and Blong 1976) and tephra mantles may be stable on slopes of up to 30° (Blong and Pain 1978). These Pleistocene deposits may be covered locally by thin ash layers originating from more recent volcanic eruptions.

The soils are therefore products of a considerable period of weathering under the climatic conditions of the sites where the tephra is deposited. In the central and western highlands, the climate is typically wet, with current mean annual rainfall varying from just less than 2000 mm to over 5000 mm (McAlpine *et al.* 1983). Above 500 m elevation, the temperature regime decreases regularly with increasing altitude. Taking the lower boundary as 1200 m (McAlpine and Quigley 1995), the altitudinal range of the highlands extends from 1200 m to 4700 m, while the principal agricultural areas are between 1400 m and 2800 m. From regression analysis of a number of PNG stations, McAlpine *et al.* (1983) estimated that annual maximum temperature decreases by 0.672°C for every 100 m rise in altitude, while annual minimum decreases by 0.535°C over the same altitude increment. On this basis, a difference of mean annual maximum temperature of 9.4°C is expected between the lowest and highest highland cultivated areas. Analysis of paleo-climate (Bowler *et al.* 1976), and evidence from pollen analysis (Walker and Flenley 1979) indicates that significantly colder conditions have prevailed at various times during the lifespan of the tephra deposits.

Because of its particulate nature, chemical weathering of volcanic ash proceeds rapidly and follows the generalised sequence illustrated in Figure 1. Initial hydrolysis of the component volcanic glass and feldspars results in a mixed gel of silicon and aluminium oxides, which is later transformed into the poorly ordered clay mineral allophane. Imogolite and gibbsite may also be formed at this stage. Besoain (1969) estimated that the time taken for volcanic ash to be transformed into dominantly allophanic material varies from decades to centuries. Subsequent transformation of allophane to halloysite is determined largely by the rate of removal of volcanic weathering products (Mohr *et al.* 1972). Thus under poorly drained conditions Andisols may still be predominantly allophanic after tens of thousands of years, whereas under more freely drained conditions, weathering proceeds more rapidly to the halloysite stage. The final transformation to kaolinite may take hundreds of thousands of years (Besoain 1969).

Tephra derived soils have high organic matter contents due to the formation of stable humus-allophane complexes (Kobo and Fujisawa 1963) and the inhibition of microbial decomposition of organic matter by allophane or its derivatives (Aomine and Kodama 1956). Cooler temperatures also favour organic matter accumulation due to slower rates of oxidation, and Pain (1982) suggested that the thickness of organic topsoil is related to tephra thickness.

Studies of toposequences of soils from Enga (Chartres and Pain 1984), and from the Mendi area of Southern Highlands Province (Radcliffe 1984 a), support the generalised sequence illustrated in Figure 2. Assuming all the soils are developed in Tomba tephra, originating from the Pleistocene eruptions of Mount Hagen, differences in soil mineralogy and resulting physical and chemical properties can be explained by the conditions under which weathering occurred, with temperature and site drainage as the main controlling factors. In soils examined at elevations of around 2400 m, the rate of weathering is limited by low temperatures and also by imperfect drainage. Allophane and other poorly ordered clay minerals were relatively abundant, with gibbsite also being recorded and observed in the field. At 1900 m warmer conditions have given rise to more friable subsoils, and to a greater proportion of halloysite, which is co-dominant with allophane, in the clay mineral assemblage. Halloysite was the dominant clay mineral in the soil at 1000 m analysed by Chartres and Pain (1984).

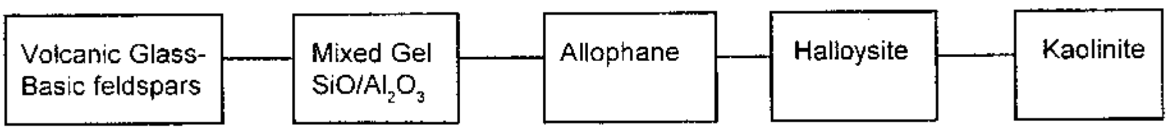
Parfitt and Mavo (1975) also detected greater proportions of allophane in high altitude (2800 m) Andisols at Tambul in Western Highlands Province, and a dominance of halloysite in Andisols developed at 1500 m near Mount Hagen.

Chartres and Pain (1984) demonstrated that the altitude related weathering sequence of tephra is also reflected in the composition of minerals in the silt fraction. The content of weatherable minerals, mainly comprising amphiboles, pyroxenes and fresh volcanic glass is highest at 2350 m, decreases at 1700 m, and is lowest at 1000 m in the toposequence of Enga soils.

In spite of their distinctive properties, Andisols have only recently been recognized as a separate order in the Soil Taxonomy classification system (Soil Survey Staff 1975), first appearing in the periodic Keys to Soil Taxonomy in 1992 (Soil Survey Staff 1992). The classification criteria are based on the proposals of the International Commission on Andisols (ICOMAND), which took account of the particular Andisols found in PNG. The soil classification adopted for the Soil Map of the World, however, recognized a separate group of 'Andosols' derived from volcanic ash (FAO/Unesco 1974).

Following Soil Taxonomy, Andisols are defined according to the presence of a combination of oxalate extractable aluminium and iron oxides (at least 2% of the fine earth fraction), high phosphate retention (>85%) and low bulk density (<0.9 $Mg.m^{-3}$).

***Figure* 2. Weathering sequence of Volcanic Ash.**



Source: Mohr *et al.* (1972).

If volcanic glass is present, the requirement for oxalate extractable Al and Fe is reduced in proportion to the volcanic glass content, and the P retention requirement is reduced to 25%. Suborders are mainly distinguished according to soil moisture regime, and most PNG highland Andisols are either Udands or Aquands depending on their drainage condition. Within these suborders, melanic (Melanaquands, Melanudands), hydric (Hydrudands), and haplic (Hapludands) great groups are common.

For the Southern Highlands Province, Radcliffe (1986) developed a practical classification of volcanic ash soils based on parent material and easily observable morphological features. Soils developed directly on airfall ash were distinguished from those formed in ash deposits which had been alluvially resorted and redeposited. A further group of soils developed from a mixture of volcanic ash and underlying sedimentaries was also identified. The airfall ash soils were subdivided into the 'olive ash soils', which are typically less weathered, imperfectly drained and found at high altitude, and the 'brown ash soils', which are normally well drained and dominate the landscape below around 2000 m. Chartres and Pain (1984) used the same terminology to distinguish between airfall ash soils in Enga, and also recognized a category of red clay soils occurring below 1200 m altitude. In the Upper Mendi area, Radcliffe (1986) described five soil series within both the olive ash soil and the brown ash soil group based on differences in horizon thickness and profile morphology.

MORPHOLOGY

Due to the tendency of allophane and similar short range order minerals to form stable bonds with organic matter, and the low rate of organic matter decomposition at high altitudes, highland Andisols typically have a well developed black epipedon, which is normally well structured and friable. The topsoil aggregates are usually very stable and the soils are comparatively resistant to erosion. The horizon thickness and organic carbon content, which normally exceeds 6%, is usually greatest at the highest altitudes. This topsoil overlies a subsoil, of which the colour, structure and degree of weathering are largely a function of altitude and site drainage. At altitudes of 2000 m and above, subsoils are usually olive and compact clays with a smeary consistence, and occasionally with a discontinuous

Table 2. **Benchmark Andisol sites.**

Soil Series (Site No).	Location	Elevation (m)	Mean Annual Rainfall (mm)[1]	Soil Group	USDA (1992) Classification
Pangia (49)	Pomiorine Experimental Farm	1550	4864	Brown ash	Acrudoxic Hydric Hapludand
Kalongia (9)	Kiburu Experimental Farm	1700	2887	Brown ash	Acrudoxic Hydrudand
Was (329)	150 m west of Tura village	1850	2887	Brown ash	Hydric Melanudand
Birop (333)	550 m west of Karil village	2270	3000-4000	Olive ash	Aquic Melanudand
Piwa (31)	Piwa Experimental	1620	2542	Alluvially resorted ash	Hapludand

Note: 1. Median annual rainfall at Mendi (1952-1983) (6°09'S; 143°39'E; 1675 m) for sites 9 and 329; Pangia (1962-1977) (6°21'S; 144°07E'; 1620 m) for site 49; and at Tari (5°52'S; 142°55'E; 1620 m) for site 31. Estimated value for site 333

Table 3. **Bulk density, porosity and moisture retention.**

Soil Series	Horizon	Bulk Density ($t\ m^{-3}$)	Total porosity (%)	Moisture retained (%w/w) at tension (MPa) 0 (saturation)	0.01	0.033	0.1	1.5	1.5 (preoven dried)
Pangia	A	0.38	82	217	187	165	154	101	33
	B1	0.70	73	104	103	97	92	59	24
	B2	0.83	68	82	82	79	76	57	28
Kalongia	A	0.54	78	155	130	122	116	82	31
	B1	0.49	80	164	154	142	138	116	23
	B2	0.75	74	99	93	88	84	62	25
Was	A	0.39	83	212	126	112	97	76	-
	B	0.49	81	165	143	131	128	109	-
	BC	0.83	71	86	78	78	73	61	-
Birop	A	0.39	82	210	192	175	164	108	26
	B	0.46	82	178	181	171	163	134	21
	C	0.90	66	73	72	63	53	42	10

Source: Adapted from Allbrooke and Radcliffe (1987).

thin iron pan (Radcliffe 1986). Below 2000 m, soils have brown firm clay subsoils with weak blocky structure, overlaying more compact clay layers.

BENCHMARK SITES

For typifying the particular physical and chemical properties of Andisols, a number of benchmark sites are selected. These sites are representative of volcanic ash soils in the highlands. Although all are located in Southern Highlands Province, they represent a range of altitudinal and rainfall conditions, and have been subjected to a consistent set of analyses which can be used for comparative purposes. Principal features of each benchmark site are given in Table 2. Detailed soil profile descriptions are given in the relevant reports of the Southern Highlands Rural Development Project (SHRDP) by Radcliffe (1984 a; 1984 b; 1984 c; 1984 d; 1986).

SOIL PHYSICAL PROPERTIES AND MOISTURE RELATIONSHIPS

Moisture regimes

Occurring mainly in the central and western parts of the highland region, highland Andisols typically have a perudic moisture regime, implying that rainfall exceeds potential evapotranspiration in all months, and that soil moisture is normally at or above field capacity. However, occasional dry periods do occur, such as in 1982 and 1997, and crops may experience moisture stress at these times. At poorly or imperfectly drained sites, an aquic moisture regime prevails.

Moisture retention and water holding capacity

Andisols have particular physical properties, some of which are used as criteria in their classification. Table 3 gives the results of bulk density measurements, calculated total porosity, and moisture retention characteristics for four benchmark soils.

Bulk densities are all within the 0.90 $Mg.m^{-3}$ threshold used as the upper limit for Andisol definition (Soil Survey Staff 1992). Values increase with depth in the profile and are probably associated with a corresponding decrease in organic matter. The highest bulk densities are encountered in the compact, little weathered C horizons. The measured particle density of 2.6 $Mg.m^{-3}$ (Allbrooke and Radcliffe 1987). Total porosity is inversely related to bulk density, and the highest porosities are encountered in the topsoils.

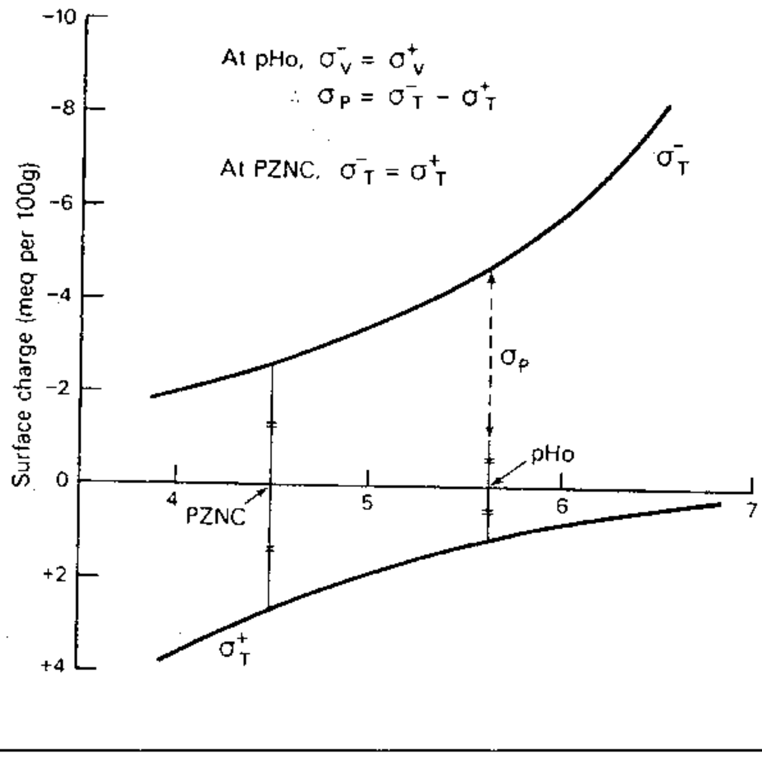
Highland Andisols have a remarkable ability to retain large amounts of water. At saturation, the A horizons all have measured moisture contents exceeding 150%, calculated on a weight basis. While retained water falls rapidly in the topsoils with increasing tension, the upper B horizons of the Kalongia, Was and Birop soils all retain more than 100% moisture at 1.5 MPa, which satisfies the criterion for Hydrudands in the USDA taxonomy. The marked fall in moisture retained if the samples are oven dried prior to analysis is another characteristic of allophanic soils and may be related to loss of pore space due to aggregation and/or the creation of hydrophobic conditions on the surfaces of allophane spherules (Allbrooke 1983).

Soil available water holding capacity (AWC) is the volumetric amount of water held in the soils between tensions corresponding to the field capacity and the permanent wilting point. In well aggregated tropical soils, a tension of 0.01 MPa is regarded as a better estimate of field capacity than the value of 0.033 MPa which has been conventionally used for temperate soils. 1.5 MPa is a generally accepted estimate of permanent wilting point. AWC can be separated into readily available and less readily available fractions according to the range in tensions at which it is held. Thus the readily available water (RAWC) can be taken as the water held between tensions of 0.01 MPa and 0.1

***Table 4.* Estimated Available Soil Water.**

Soil type	Available Water (mm) in soil depth (m)		Readily Available Water (mm) in soil depth (m)	
	0.3 m	1.0 m	0.3 m	1.0 m
Pangia	97	301	34	82
Kalongia	82	265	28	97
Was	60	172	33	74
Birop	99	292	33	122

***Figure 3.* Typical negative and positive charge curves in a mixed variable/permanent charge system.**



MPa. RAWC provides a rough estimate of the water which can be depleted by the crop without any moisture stress. Table 4 presents estimates of the available and readily available moisture held in the top metre and the top 0.3 m of the soils analyzed. AWC and RAWC are calculated from the weight/weight percentages in Table 3 by subtraction of moisture contents at the appropriate tensions, and by multiplying by the bulk density. Weighted volumetric moisture contents for standardised depths are derived from AWC and RAWC of the component soil horizons, which are weighted according to thickness.

The data in Table 4 can be used to estimate tolerance of crops to drought. Shallow rooting crops, and crops with a rooting system confined to soil mounds can be assumed to extract most of their moisture from the top 0.3 m of soil, while deeper rooting crops such as maize and coffee may extract moisture to a depth of approximately 1.0 m. On the basis of a mean daily evapotranspiration of 3.0 mm, which is an average estimate for the Upper Mendi area (Radcliffe 1986), shallow rooting crops would deplete readily available moisture reserves in approximately 10 days, while deeper rooting crops could be expected to survive for considerably longer (25-40 days) without moisture stress. In the western part of the highlands, rainless periods of more than 10 days are rare, and it is probable that moisture stress is only a serious yield limiting factor during the regional droughts which occur approximately every 10 years (McAlpine *et al.* 1983).

CHEMICAL PROPERTIES

Ion exchange and variable charge

Electric charge at the surface of clay particles arises either from isomorphous substitution in the lattice of crystalline clay minerals, or from adsorption and/or desorption of protons at the soil-solution interface. The former type of charge is permanent and is unaffected by soil solution conditions, but the charge associated with protonation and deprotonation of the particle surface is highly dependent on the concentration and the pH of the contact electrolyte.

The type and amount of charge is a function of the clay mineralogy and organic matter content. With a dominance of short range order clay minerals and high organic matter content, the Andisols of the PNG highlands are extreme examples of variable charge soils. Conventional methods of measuring cation exchange capacity, at a fixed pH and electrolyte concentration, are inadequate to characterise the ion exchange properties of such soils. Such characterisation is important in determining how the soils are managed, and it can be achieved by plotting the distribution of total positive and total negative charge when the soil is in equilibrium with an electrolyte of standard concentration and varying pH (Gillman 1984).

Typical negative and positive charge curves in a mixed permanent-variable charge system are shown in Figure 3. pH_0 is the pH at which the total positive variable charge equals the total negative variable charge and the net variable charge is zero. Any net charge at pH_0 is therefore permanent charge, and the difference between soil pH and pH_0 ($pH-pH_0$) determines the magnitude of charge under field conditions. At the point of zero net charge (PZNC) the total net charge, including both variable and permanent components, is zero.

Table 5 summarises the charge characteristics of the benchmark Andisols (Table 2). The total negative and positive charge is given at the prevailing soil pH, together with the proportional distribution of permanent charge and variable charge. The rate coefficient describes the steepness of the exponential curve relating charge to pH, and is equivalent to the term 'b' in the relationship in equation (1). A high rate coefficient indicates greater tendency for negative charge to increase with increasing pH, and a greater tendency for positive charge to decrease with increasing pH.

$$\sigma_T = a \times e^{b(pH0-pH)} \qquad (1)$$

where 'a' is the total charge (σ_T) at pH_0, 'e' is the base of the natural logarithm, and 'b' is the gradient of the exponential curve.

In the study summarised in Table 5, curves of the form expressed in Equation (1) accounted for between 88% and 100% of the variation in negative charge and between 71% and 99% of the variation in positive charge with pH.

The results in Table 5 show that all the Andisols analysed have substantial variable charge compo-

***Table 5.* Charge characteristics at Soil pH (adapted from Radcliffe and Gillman 1985).**

Soil Series	Horizon	pH ($CaCl_2$)	pH_0	Negative charge (σ^-) (cmol kg^{-1} soil) at soil pH	Negative charge Rate Coefficient	Positive charge (σ^+) (cmol kg^{-1} soil) at soil pH	Positive charge Rate Coefficient	Permanent Charge (σ_p) (cmol kg^{-1} soil)	variable negative (σ_v) at soil pH (%)
Pangia	A	4.7	4.7	5.5	0.47	0.7	0.32	-4.8	13
	AB	4.9	4.6	4.0	0.56	0.8	0.51	-2.4	40
	B	5.0	5.5	2.8	0.59	1.4	0.73	-2.8	0
Kalongia	A	4.6	4.5	6.5	0.44	1.4	0.31	-4.8	26
	B1	5.0	5.2	3.7	0.62	2.3	0.62	-2.2	41
	B2	5.4	6.0	3.2	0.68	3.2	0.59	-2.5	22.
Was	A1	5.1	4.0	16.0	0.51	1.0	0.55	-7.3	54
	A2	5.0	4.1	12.4	0.44	0.5	0.49	-7.6	39
	B	5.3	5.7	3.4	0.63	2.0	0.78	-3.0	12
Birop	A1	4.7	4.3	7.1	0.56	1.0	0.40	-4.6	35
	A2	4.8	4.6	6.6	0.47	1.1	0.68	-4.7	29
	C	5.7	6.2	1.1	1.32	2.6	0.63	+0.7	36
Piwa	A	4.7	3.7	4.8	0.43	1.1	0.56	-1.1	77
	B1	5.0	3.8	4.2	0.39	1.3	0.64	+0.1	100
	B2	4.9	3.1	12.9	0.16	0.5	1.11	-5.7	56

***Table 6.* Phosphorus status and sorption characteristics (adapted from Moody and Radcliffe 1986).**

Soil Series	Horizon	Extractable P (Olsen) (mg kg^{-1})	Extractable P (Colwell) (mg kg^{-1})	P retention (%)	PBC (l kg^{-1})	P sorbed at solution conc. 200µg l^{-1} (mg kg^{-1})
Pangia	A	4	15	96	754	975
	AB	2	12	97	638	1220
	B	2	5	96	949	1820
Kalongia	A	3	13	97	1012	1380
	B1	1	4	97	1105	2250
	B2	1	2	97	1451	3300
Was	A1	2	32	98	604	880
	A2	2	28	98	623	1070
	B	2	22	99	1237	2520
Birop	A1	2	12	99	706	1450
	A2	2	11	99	1219	1675
	C	1	4	99	1021	1800
Piwa	A	3	14	97	485	920
	B1	2	7	95	485	875
	B2	9	21	83	324	630

nents. The soils formed from airfall ash display clear trends in the factors affecting charge distribution, showing marked increases with depth in pH_0, the rate coefficients of the charge curves and anion exchange capacity (AEC), and corresponding decreases in permanent negative charge and CEC. No such trend is apparent in the Piwa Series, in which profile development has been influenced by alluvial action.

Soil surface charge is determined by clay mineralogy and organic matter content, and in soils dominated by short range order minerals, the content of active sesquioxides and organic carbon may be expected to exert a dominant influence. Radcliffe and Gillman (1985) showed correlations of pH_0 with free Fe_2O_3, free Al_2O_3 and organic carbon, which were significant at the 0.1% level over the range of Southern Highlands Andisols tested. Organic carbon and free Fe_2O_3 were also significantly correlated with CEC, AEC and permanent charge.

The results in Table 5 show that, with the exception of the Was topsoil and the poorly drained Piwa Series, all the soils have limited ability to retain cations at their current pH. This limited surface negative charge limits nutrient supply under unfertilized conditions, and limits the efficiency with which crops can respond to inorganic fertilizer.

Phosphorus sorption

Phosphorus is usually the most limiting nutrient in highland Andisols. Although total P is often high, availability is limited by the high sorption capacities of these soils. Sorption curves, derived by equilibrating the soil with different concentrations of phosphate in solution, can be used to describe the P status of such soils. The most useful parameter for quantitative comparison of P sorption is the phosphate buffer capacity (PBC), which is the slope of the linear regression equation relating P sorbed to $\log_{10}$ supernatent P concentration for concentrations less than 100 $\mu g\ P.l^{-1}$ A high PBC indicates high rates of P sorption.

Table 6 compares PBC and other factors used to describe the P status of the five benchmark Andisols listed in Table 2. 'P-retention' (Blakemore *et al.* 1981) is another measure of P sorption which is used as a parameter for classification of Andisols (Soil Survey Staff 1992).

The results in Table 6 indicate that extractable P is low, particularly when measured by the Olsen method. PBC of all soils is high, and the soils formed from airfall ash have higher values than the alluvially resorted Piwa Series. The airfall ash soils also show an increase in PBC from the A horizon to the B and C horizon.

The figures for P sorbed at a solution concentration of 200 $\mu g.l^{-1}$ exhibit a similar trend to the PBC figures. Parfitt and Mavo (1975) recorded values of between 380 and 1200 $mg.kg^{-1}$ P sorbed for Andisols from Aiyura (Eastern Highlands), Kuk and Tambul (Western Highlands), and similar results were recorded by Macfarlane (1974) and Fox *et al.* (1974) for Andisols from St. Vincent and Hawaii respectively.

With the exception of the lower subsoil of the Piwa Series, P retention figures are all high. A plot of PBC against P retention indicates that retention values of more than 95% are insensitive to changes in PBC. Hence, the use of P retention as a comparative measure may not be appropriate in very highly sorbing soils (Moody and Radcliffe 1986).

Correlation of PBC with various forms of extractable Al, Fe and Si suggested that P sorption sites are mainly associated with allophane, allophane-like compounds and Al hydrous oxides. Fe in association with organic complexes also accounts for some of the sorption sites. However, the results presented in Table 6 indicate an increase in PBC from the Birop Series to the Was and Kalongia Series, which is the converse of that expected from their relative intensity of weathering and allophane content.

Nutrient status

The chemical fertility of Andisols is generally poor and phosphorus is not the only limiting nutrient. The availability of potassium is affected by the usually low content of cations at the prevailing soil pH (Table 5), and high levels of exchangeable aluminium may present constraints to some crops. Nitrogen levels are usually high in the organic rich topsoils but availability may sometimes be limited due to high carbon:nitrogen ratios. Boron deficiency is widespread (Bourke 1980; Radcliffe 1986) and local deficiencies of managanese, zinc and copper were noted in Southern Highlands (Radcliffe 1986).

MANAGEMENT UNDER TRADITIONAL AGRICULTURAL SYSTEMS

The favourable physical properties of Andisols, and their tendency to occur on less steeply sloping sites where tephra is easily accumulated, has favoured their selection for cultivation in the PNG highlands. In wetland environments, where Andisols may occur in association with Histosols, rural population densities are as high as 200 persons.km^{-2} (Wood 1984), while densities of up to 120 persons.km^{-2} have been recorded in purely dryland environments (Crittenden *et al.* 1988).

A number of traditional systems of management are adopted in different parts of the highlands, in different topographic and altitudinal locations and by different ethnic groups (Wood and Humphreys 1982). Most management systems address the fertility constraints of Andisols by fallowing, the use of mounds with compost, or by a combination of these techniques. These techniques are not merely a response to declining fertility, however, but also address such constraints as increasing weed and nematode infestation (fallowing) and frost protection (mounding). Mounds tend to be larger in higher altitude sites in the western part of the highlands, particularly in Enga Province (Waddell 1972).

Sweet potato is the dominant subsistence crop grown on Andisols and, as a tuber, has a relatively high demand for K and a low demand for P. A large number of traditional and introduced vegetable crops are used to supplement the diet, and these may be grown either separately from sweet potato or in mixed gardens. Pigs are usually tethered in fields where they are allowed to forage on old sweet potato mounds. This practice may have some benefits in nutrient enhancement by manure, but may increase soil erodability.

Semi-permanent cultivation systems on Andisols have proved to be sustainable over periods of at least hundreds of years, often on slopes with gradients which would be regarded as excessive for cultivation of other soil types. The combination of high aggregate stability and infiltration in the topsoil and usual high permeability in the subsoil results in high resistance to erosion or physical soil degradation, and Wood (1984) reported little change in physical properties with cultivation. Decline in chemical fertility with cultivation time has been demonstrated (Wood 1984), but Andisols are relatively more resilient to fertility decline than non-Andisols in comparable situations (Bleeker 1983). However, Andisols are not immune from degradation, and the rising demands of a more rapidly increasing population are imposing unprecedented strains on capacity of the traditional land use systems. Shortening fallow periods are likely to result in lower yields and less material for composting, as composting rate is partly determined by the vine yield of the previous crop (Floyd *et al.* 1988), and there is a danger that increasingly marginal land may be cultivated. There is therefore an urgent need to investigate the opportunities for improving the productivity of land use on a sustainable basis.

CONSTRAINTS AND POTENTIAL FOR IMPROVED MANAGEMENT

The generally favourable physical properties of Andisols have been noted in the preceding discussion and the principal constraints to increased production through improved management are related to their chemical properties. The specific chemical properties limiting production on highland Andisols are:

* low availability and high sorption of phosphorus
* potassium and micronutrient deficiencies
* low exchangeable bases and low cation exchange capacity

Amelioration of some of these constraints has been addressed by fertilizer trials carried out on experimental stations and on farmers' fields. The results of these trials have been reviewed from an Andisol perspective by Kanua (1995), while other papers in the present publication (e.g. Harding in this issue) deal with nutrient management from a crop perspective for sweet potato and coffee respectively. The present discussion draws on the results of these trials, on relevant experience outside PNG, and on theoretical considerations in addressing the principal constraints listed above.

Amelioration of P deficiency

The universally low available P and high P sorption in highland Andisols, confirms the observation from fertilizer experiments that P is the most critically limiting nutrient (Goodbody and Humphreys

1986; Floyd *et al.* 1988). Adsorption isotherms suggest that massive fertilizer applications are required to achieve a P concentration of 200 $\mu g.l^{-1}$ in the soil solution, which may be required to achieve maximum crop yields. For example, for the Southern Highland Andisols in Table 6, between 900 and 1400 $\mu g.g^{-1}$ of P would have to be added to the topsoil to achieve the required solution concentration. Assuming a 20 cm depth of incorporation this would be equivalent to 4100 to 6700 kg of triple superphosphate per hectare. Kimber (1980) recorded P responses of sweet potato at applications of up to 6000 kg superphosphate per hectare, and Floyd *et al.* (1988) recorded yield responses at application rates of up to 1000 kg P per hectare.

Such application rates are clearly beyond the resources of the small farmer and are also unlikely to be economic to commercial producers. In spite of high P retention, not all added P is immediately sorbed and it appears that significant amounts of added P are available in the soil solution before the high sorption demand is quenched. Although demonstrating continuing responses to high P applications, field experience has also shown that crops respond significantly to much lower applications. Goodbody and Humphreys (1986) recorded a significant linear correlation between first harvest sweet potato yield and available soil P, and Floyd *et al.* (1988) demonstrated a curvilinear response of sweet potato to fertilizer P, with greater incremental increases at lower fertilizer application rates. In spite of these observation, Floyd *et al.* (1988) calculated that P fertilization was not economically viable on any of the Andisols tested.

Efficiency of phosphate fertilizer uptake may be improved by band placement or by the use of forms of phosphate with slow release characteristics, such as rock phosphate. Band placement works on the principle of saturating adsorption sites within the band, with a greater release of phosphate within the area accessible to crop roots. An alternative technique would be to apply an initial massive fertilizer dose, with the expectation of residual effects from P desorption in subsequent years. Floyd *et al.* (1988), however, found poor crop responses to residual P in the Southern Highlands.

Vesicular arbuscular mycorrhizae (VAM) form symbiotic associations with plant roots and facilitate the uptake of phosphorus. Floyd *et al.* (1988) found that mycorrhizal infection increased with lower applications of P fertilizer but decreased at higher rates. Innoculation of soils with particular strains of VAM as an aid to improving phosphorus use efficiency was proposed by Abbott and Robson (1982).

Amelioration of K and micronutrient deficiencies

Highland Andisols are typically low in potassium and in several micronutrients. Correcting the K deficiency in highlands Andisols is more straightforward than solving the problems of P fixation. Most crops grown on highland Andisols show responses

Table 7. **N, P and K contents of organic materials at recommended application rates for sweet potato.**

Material	Total N ($kg\ ha^{-1}$)	Total P ($kg\ ha^{-1}$)	Total K ($kg\ ha^{-1}$)	Application rate ($t\ ha^{-1}$)
Coffee pulp	70	5	140	30
Ischaemum grass	75	10	75	20
Pig manure	85	50	60	15
Azolla pinnata	40	5	30	30

Source: Bourke (1982), D'Souza and Bourke (1986 b).

to K fertilizer, and Kimber (1980) gives a recommended application of 160 kg muriate of potash per hectare rate for PNG highland mineral soils. On Andisols of the Nembi Plateau (Southern Highlands Province), D'Souza and Bourke (1986 a) observed good responses of sweet potato to K application rates of 75 $kg.ha^{-1}$, and also demonstrated that the response to organic fertilizers was strongly correlated to their K content (D'Souza and Bourke 1986 b).

For farmers operating at a subsistence or marginal commercial level, organic materials are usually the most convenient sources of K. Table 7 summarises the N, P, and K contents of organic materials at the recommended application rates for sweet potato. Coffee pulp, pig manure and grass compost are particularly rich sources of K. Grass and old sweet potato vines are normally incorporated into mounds in the traditional sweet potato based farming systems, and experimental evidence suggests that compost applications at much higher rates than those traditionally used, give good yield responses (Bourke 1982; D'Souza and Bourke 1986 b, Floyd *et al.* 1988). It is significant to note that recommendations to increase the amount of some forms of compost, such as grass, may place unacceptable additional burdens on the workload of women (Floyd *et al.* 1988).

It should be noted that on soils with a relative as well as an absolute shortage of K (where K constitutes less than 2% of total exchangeable bases), liming to raise soil pH will exacerbate K deficiency unless the lime is accompanied by a correspondingly high rate of K fertilizer. The review of Sanchez (1973) of South American volcanic soils is relevant to the PNG highlands situation.

Little experimental work has been carried out on the amelioration of micronutrient deficiencies. Bourke (1980) suggests that coffee pulp or borax fertilizer may be used to correct boron deficiency.

Raising the base status and cation exchange capacity

The principal problem resulting from the variable charge characteristics of highland Andisols is the low CEC and low content of exchangeable bases at the ambient soil pH. Raising the CEC is an approach to this problem, and the results of ion exchange analysis indicate that this may be achieved by increasing the negativity of (pH_0 - pH), either by raising the soil pH or by decreasing pH_0. Application of the regression curves describing variation of negative charge with pH for the Southern Highlands soils (Table 5 and Equation (1)) suggests that increasing (pH_0 - pH) by 0.5 units would result in an increase in CEC by between 1.5 and 4.6 $cmol.kg^{-1}$ in the airfall ash soils, raising the CEC to 7-10 $cmol.kg^{-1}$ in the Pangia, Kalongia and Birop Series.

Raising the pH of highly variable charge soil by liming is rarely feasible because of the high buffering capacity as pH departs from pH_0 (Uehara and Gillman 1981). Furthermore, the addition of calcium to soils in which potassium is commonly only marginal would exacerbate K deficiency, particularly in tuber crops such as the sweet potato staple.

Lowering pH_0 depends on blocking some of the positively charged sites by adsorbed anions. The strong relationship of pH_0 with organic carbon would suggest that additions of organic matter may be effective in lowering pH_0 (Uehara and Gillman 1981). Although the scope for incorporating more organic matter into soils which already have an average topsoil organic carbon content of around 11% (Radcliffe 1986) may be limited, additions of compost are a feature of the traditional farming system, and some of its beneficial effects may be attributable to increasing cation availability by lowering pH_0. Additional factors, such as increased soil temperature due to enhanced microbial activity, may however also be important. Inorganic anions, such as phosphate and silicate, could also be used as a means of lowering pH_0. Highland Andisols commonly suffer severe phosphorus fixation, and addition of phosphate as a plant nutrient may have additional benefits in raising the CEC.

CONCLUSIONS - FUTURE RESEARCH NEEDS

Highland Andisols are elements of complex agroecosystems which are the basis for the livelihoods of more than 700,000 rural Papua New Guineans (Table 1). One of the main challenges is to bring together the results of experimental work by soil scientists, agronomists and social anthropologists to provide a better understanding of how these ecosystems operate, and to determine their sustainability and resilience as land resources come under increasing pressure due to the growing needs of a rapidly expanding population.

While taking account of specific soil-related problems, it can be argued that future research on highland Andisols should be integrated within these systems, which may be farming systems or natural ecosystems in forested areas. Such an approach should maximize the application of results, promote synergy with research in other disciplines and more effectively contribute to the sustainable development of the ecosystem.

Within each overall ecosystem, a number of subsystems operate, and it is important to recognize the interaction of component processes when designing an experimental programme and evaluating the results. For example, a sweet potato - Andisol combination may be regarded as a subsystem within a particular farming system. On the basis of soil analysis, observation of crop performance and farmer experience, an experimental programme may be designed to address identified constraints. Due to the interrelationship of the factors governing soil fertility, a particular treatment, such as compost application may have impacts on a number of different soil properties, such as available N, P and K, pH_0, CEC, available water holding-capacity, soil temperature etc. Up to the present, fertilizer experiments have rarely attempted to record these multiple impacts or to explain their possible influence on crop yield.

Within this recommended systems approach to highland Andisols, a number of priority research topics are identified, and these are listed as follows:

* Characterization and classification. While recognising Andisols as a separate order, the latest version of Soil Taxonomy (Soil Survey Staff 1994) is an inefficient method of distinguishing soils at a local level.
* Interactions between soil nutrients and inorganic/ organic fertilizers
* Role of vesicular arbuscular mychorrizae in P uptake
* Trace element responses
* Composting in mounds: temperature effects/ influ-ence on microbial activity, nutrient mobilization and crop yield.

REFERENCES

ABBOTT, L.K. and ROBSON, A.D. (1982). The role of vesicular arbuscular mycorrhizal fungi in agriculture and the selection of fungi for innoculation. *Aust. J. Agric.Res.*33: 389-408.

ALLBROOKE, R.F. (1983). Some physical properties of allophane soils from North Island, New Zealand. *N.Z. J. Sci.* 26: 481-492.

ALLBROOKE, R.F. AND RADCLIFFE, D.J. (1987). Physical properties of Andepts from the Southern Highlands of Papua New Guinea. *Geoderma* 41: 107-109.

AOMINE, S. and KODAMA, I. (1956). Clay minerals of some arable soils in Miyazaki Prefecture. *J. Fac. Agric. Kyushu University.* 10: 325-344.

BESOAIN, E. (1969). Mineralogia de las argillas de suelos derivados de cenizas volcanicas de Chile. In *Suelos derivados de cenizas volcanicas de America Latina.* Centro de Ensenanza e Investigacion del IICC, Turrialba, Costa Rica.

BLAKEMORE, L.C., SEARL, P.L., and DALY, B.K. (1981). Methods for chemical analysis of soils. *New Zealand Soil Bureau Scientific report* 10A. DSIR, Lower Hutt, New Zealand.

BLEEKER, P. (1983). Soils of Papua New Guinea. CSIRO/ Australian National University Press, Canberra.

BLONG, R.J. and PAIN, C.F. (1978). Slope stability and tephra mantles in the Papua New Guinea Highlands. *Geotechnique* 28(2): 206-210.

BOURKE, R.M. (1980). Boron deficiency is widespread in the highlands. *Department of Primary Industry. Technical Report* No. 83/3, Port Moresby.

BOURKE, R.M. (1982). Growing sweet potato for sale in the highlands. *Harvest* 8 (2): 47-58.

BOWLER, J.M., HOPE, G.S., JENNINGS, J.N., SINGH, G. and WALKER, D. (1976). Late Quaternary climates of Australia and New Guinea. *Quat. Res.* 6: 359-394.

CHARTRES, C.J. and PAIN, C.F. (1984). A climosequence of soils on late Quaternary volcanic ash in highland Papua New Guinea. *Geoderma* 23: 131-155.

CRITTENDEN, R., FLOYD, C.N., LEFROY, R.D.B., ANDERS, M.A., D'SOUZA, E., and LEHMAN, D. (1988). Gardening activity, food supply and nutritional status in the Southern Highlands of Papua New Guinea. *Ecology of Food and Nutrition.* 21: 45-68.

D'SOUZA, E.J. and BOURKE, R.M. (1986 a). Intensification of subsistence agriculture on the Nembi Plateau. 1. General introduction and inorganic fertilizer trials. *PNG J. Agric. For. Fish.* 34(1-4) 19-28.

D'SOUZA, E.J. and BOURKE, R.M. (1986 b). Intensification of subsistence agriculture on the Nembi Plateau. 2. Organic fertilizer trials. *PNG J. Agric. For. Fish.* 34(1-4): 29-39.

FAO/UNESCO (1974). FAO-Unesco Soil Map of the World. Vol 1. Legend. Unesco, Paris.

FLOYD, C.N., LEFROY, R.D.B. and D'SOUZA, E.J. (1988). Soil fertility and sweet potato production on volcanic ash soils in the highlands of Papua New Guinea. *Field Crops Res.* 19 1-25.

FOX, R.L., NISHIMOTO, R.K., THOMPSON, J.R. and DE LA PENA, R.S. (1974). Comparative external phosphorus requirements of plants growing in tropical soils. *Trans. Congr. Int. Soc Soil Sci., 10th. Moscow.* 4: 232-239.

GILLMAN, G.P. (1984). Using variable charge characteristics to understand the exchangeable cation status of oxic soils. *Aust. J. Soil Res.* 17, 71-80.

GOODBODY, S and G.S. HUMPHREYS, G.S. (1986). Soil chemical status and prediction of sweet potato yields. *Trop. Agric. (Trinidad)* 63 (2): 209-211.

KANUA, M.B. (1995). A review of properties, nutrient supply, cultivation and management of volcanic soils, with particular reference to Papua New Guinea. *PNG J. Agric. For. Fish.* 38(2) 102-123.

KIMBER, A.J. (1974). Personal communication, quoted in Parfitt and Mavo (1975).

KIMBER, A .J. (1980) Fertilizing sweet potato on mineral soils in the Highlands. *Highland Agricultural Experimental Station Tech. Bull.* No. 14, Aiyura.

KOBO, K. and FUJISAWA, T. (1963). Studies on the clay humus complex (part 3). Adsorption of humic acid by clay. *J. Sci. Soil and Manure*, Japan 34: 13-17.

McALPINE, J.R. and QUIGLEY, J. (1995). Natural Resources, Land Use and Population Distribution of Papua New Guinea. Summary statistics from PNGRIS. PNGRIS Report No. 7. CSIRO/AusAID; Canberra.

McALPINE, J.R., KEIG, G. and FALLS, R. (1983). Climate of Papua New Guinea. CSIRO/ ANU Press, Canberra.

MACFARLANE, M. (1974). Phosphate studies on volcanic ash soils from St Vincent. Ph.D. thesis, University of the West Indies, St Augustine, Trinidad.

MOHR, E.C.J., VAN BAREN, F.A. and VAN SCHUYLENBORGH, J. (1972). Tropical Soils A comprehensive study of their genesis. van Hoeve, The Hague.

MOODY, P. AND RADCLIFFE, D.J. (1986). Phosphorus sorption by Andepts from the Southern Highlands of Papua New Guinea: *Geoderma* 37:137-147.

PAIN, C.F. (1982). Enga Soils: Reconnaissance soil map and explanatory notes. In *Enga Yaaka Lasemana*. (K.K. Talyaga and B. Carrad, Eds.). Supplementary Volume. National Planning Office, Waigani.

PAIN, C.F and BLONG, R.J. (1976). Late Quaternary tephras around Mount Hagen and Mount Giluwe, Papua New Guinea. pp. 239-251. In Quaternary volcanism in Australasia. R.W. Johnson (Ed.). Elsevier.

PARFITT, R.L., and MAVO, B. (1975). Phosphate fixation in some Papua New Guinea soils. *Science in New Guinea*. 3: 179-190.

RADCLIFFE, D.J. (1984 a). The land resources of Kiburu Experimental Farm. AFTSEMU Technical Report. Southern Highlands Rural Development Project, Mendi.

RADCLIFFE, D.J. (1984 b). The land resources of Piwa Experimental Farm. AFTSEMU Technical Report. Southern Highlands Rural Development Project, Mendi.

RADCLIFFE, D.J. (1984 c). The land resources of Pomiorine Experimental Farm. AFTSEMU Technical Report. Southern Highlands Rural Development Project, Mendi.

RADCLIFFE, D.J. (1984 d). The land resources of Kuma Experimental Farm. AFTSEMU Technical Report. Southern Highlands Rural Development Project, Mendi.

RADCLIFFE, D.J. (1986). The land resources of Upper Mendi. *Department of Primary Industry Research Bulletin* No. 37 (2 vols.), Port Moresby.

RADCLIFFE, D.J. and GILLMAN, G.P. (1985). Surface charge characteristics of volcanic ash soils from the Southern Highlands of Papua New Guinea. *Catena* Supplement 7. *Volcanic Soils: Weathering and landscape relationships of soils on tephra and basalt.*

SANCHEZ, P.A. (1973). (ed.). A review of soils research in tropical Latin America. Soil Science Dept., North Carolina State University, Raleigh, NC, USA.

SOIL SURVEY STAFF, (1975). Soil Taxonomy. A basic system of soil classification for making and interpreting soil surveys. *Agriculture Handbook* No. 436. Soil Conservation Service, U.S. Dept. Agric., Washington D.C.

SOIL SURVEY STAFF, (1992). Keys to Soil Taxonomy. *SMSS Technical Monograph* No. 19. 5th Edition. Pocahontas Press Inc., Blacksburg, Virginia.

SOIL SURVEY STAFF, (1994). Keys to Soil Taxonomy. *SMSS Technical Monograph* No. 19. 6th Edition. Pocahontas Press Inc., Blacksburg, Virginia.

UEHARA, G., and GILLMAN, G.P. (1981). The mineralogy, chemistry and physics of tropical soils with variable charge clays. Westview Tropical Agriculture Series. No. 4., Westview Press, Boulder, Colorado

WADDELL, E. (1972). the mound builders. Agricultural practices, environment and society in the central highlands of New Guinea. 253 pp. University of Washington Press, Seattle.

WALKER, D. and FLENLEY, J.R. (1979). Late Quaternary vegetational history of the Enga province of upland New Guinea. *Philos. Trans. R. Soc.* London. 286: 265-344.

WOOD, A.W. (1984). Land for tomorrow: Subsistence agriculture, soil fertility and ecosystem stability in the New Guinea Highlands. Unpublished PhD thesis. University of Papua New Guinea, Waigani.

WOOD, A.W. and HUMPHREYS, G.S. (1982). Traditional soil conservation in Papua New Guinea. pp 93-114 in *Traditional conservation in Papua New Guinea. Implications for Today.* L. Morauta, J. Pernetta, and W. Heaney Eds. IASER Monograph 16. Institute of Applied Social and Economic Research, Port Moresby.

A REVIEW OF COFFEE NUTRITION RESEARCH IN PAPUA NEW GUINEA

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ABSTRACT

Research on coffee nutrition conducted in Papua New Guinea between 1954 to 1998 is reviewed and deals with arabica coffee with and without shade and under both smallholder and plantation conditions. Coffee leaf nutrient contents can respond within eight months to fertilizer applications but seasonal variation in leaf nutrient contents is large. Leaf nutrient contents are generally higher in shaded coffee. Unshaded coffee nearly always responds to N fertilizers although two or more years are required before the response occurs. Without N fertilizers, coffee will die within a few years when there is no shade. Large applications of N have, however, been shown to strongly acidify the soils which is accompanied by a decrease in exchangeable cations. The application of K fertilizers is beneficial in some soils although negative effects on the uptake of Ca and Mg have been found. In some soils positive reponses to P fertilizers occur with young coffee but no significant response to Mg fertilizers have been recorded in Papua New Guinea. Shaded coffee rarely responds to N fertilizers and negative effects have also been found. Shaded coffee commonly responds to K fertilizers up to 400 kg K_2O/ha. Positive reponses to Zn and B have also been recorded. Although substantial yield increases may be obtained with inorganic fertilizer applications, recycling of coffee litter, prunings and processing waste products, can reduce fertilizer applications by up to 20%.

Keywords: *arabica coffee, nutrition, fertiliser, shade, waste products, plantations, smallholder gardens, Papua New Guinea.*

INTRODUCTION

Coffee is PNG's most important rural export earner, and is the major source of income for one-third of the country's population. About 1 million bags (or 60,000 tonnes) of green bean are exported each year. Both arabica (*Coffea arabica* L.) and robusta (*Coffea canephora* Pierre ex Froehner) coffee are grown in PNG. The main arabica and robusta coffee growing areas in PNG have been identified by Harding (1985a). Robusta coffee accounts for less than 5% of PNG's total coffee production, and is grown below 600 m a.s.l. The bulk of PNG's coffee is arabica coffee, and is grown above 600 m a.s.l. in thirteen of the nineteen Provinces. More than 80% of the total production is grown by smallholders, of which there are approximately 280,000, about 15% is grown by around 100 plantations, and the balance is grown by several hundred managed blocks. The total area under coffee probably exceeds 55,000 ha equivalent of pure stand coffee (Robinson 1983).

Following the Second World War, coffee was not an immediate priority for the Department of Agriculture. However, as the coffee industry grew, the need for coffee research was recognised by the Department. Thus, formal coffee research in PNG was initiated by the Department of Agriculture in 1954 (Carne and Charles 1966). The arabica coffee research programme was based at Aiyura Highlands Agricultural Experiment Station (HAES), and supplemented by trials at the Agricultural Extension Centres at Goroka (EHP) and Korn Farm (WHP). A relatively small robusta coffee research programme was based at Kerevat LAES, with a few activities undertaken at Saramandi Research Station (East Sepik Province) and Bubia Research

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Station (Morobe Province), but this ceased in 1980 (Byrne 1984). Coffee research continued to be a priority throughout the 1950s and 1960s, but during the seventies other commodities, particularly food crops, were given a higher priority by the Department. With limited resources available, the Department considered that cash crop research should be supported by the cash crop industries themselves. Thus, in 1981 the Coffee Industry Board established a small coffee research department, based at its Headquarters in Goroka.

In early 1986, the PNG Coffee Research Institute (CRI) was established at Aiyura HAES, using land and facilities provided by the Department, but funded by a "research cess" collected by the CIB from every kg of green bean coffee exported. The old coffee trials were adopted by the CRI, and a new coffee research programme commenced in 1986. The CRI subsequently established a Highlands Substation at Panga, Western Highlands Province in 1988, and a Lowlands Substation at Omuru, Madang Province in 1993. Coffee nutrition research in PNG has therefore been undertaken almost exclusively with arabica coffee, and in this review the word coffee may be read as arabica coffee.

Initially, since the coffee industry in PNG was primarily plantation based, and most plantations grew shaded coffee, coffee research was undertaken in shaded plantation coffee conditions at Aiyura, Goroka and Korn Farm. Later, as plantation managers removed their shade trees to increase coffee yields, research was also undertaken in unshaded plantation conditions, on Aiyura and also several plantations. Little or no research has been carried out under traditional smallholder conditions, since these were seen as a low-input, low-output, management system which was apparently self-sustaining. Recent modelling of N dynamics by Harding (1994) has tended to confirm this to be true, at least in the absence of major pests or diseases. However, the outbreak of coffee leaf rust (*Hemileia vastatrix*) in 1986, necessitated the rehabilitation of thousands of traditional smallholder coffee gardens. Such improved coffee gardens, with reduced shade, formal pruning systems, and higher yields, were no longer necessarily self-sustaining. Thus, in 1986 the CRI began coffee nutrition studies in rehabilitated smallholder coffee gardens.

THE SOIL UNDER COFFEE

Harding (1984) and Harding (1985 b) have described the arabica and robusta coffee soils of PNG respectively. The most common coffee soils are deep, well to imperfectly drained, fine textured, ash-derived soils with high P-retention capacities and high organic matter contents (Hydrandepts, Eutrandepts and Dystrandepts which are all classified as Andisols in the recent USDA Soil Taxonomy); deep, well to imperfectly drained, fine textured, non-ash soils with low to moderate P-retention capacities and high organic matter contents (Humitropepts, Eutropepts and Dystropepts); poorly to very poorly drained, fine textured, non-ash soils with high organic matter contents (Tropaquepts); and shallow, well to imperfectly drained, medium to coarse textured, soils on steep slopes (Troporthents). The Hydrandepts and Humitropepts in particular, are also acidic to strongly acidic, with a low base saturation.

Hart and Southern (1969) described coffee soil sample preparation and analytical methods. Harding (1986) compiled guidelines on collecting and preparing coffee soil samples, analytical methods, and interpretation of the analytical results (Table 1).

SOIL RESPONSES TO NUTRIENT APPLICATIONS

Shaded coffee

Parfitt (1976) recorded an increase in total soil nitrogen under *Casuarina oligodon* of 0.015-0.018% per year. Thiagalingam and Fahmy (1981) recorded increases in both soil nitrogen and carbon levels under mature *Casuarina oligodon* when compared with levels under young trees. During the first five year cycle (1986-1991) of a smallholder fertiliser trial in the Eastern Highlands (SPN 2.01), no significant fertiliser effects on soil properties were recorded. During the second production cycle (1991-1997) however, soil exchangeable K levels declined in the absence of K fertiliser (Hombunaka unpublished data).

In a series of nutritional studies (Harding 1993 a, b, c) this author (Harding (1993 c) reported that in a fertiliser trial under shaded coffee on Koban Plan-

Table 1. **Ctritical levels for interpretetation of Soil Analytical Data (Source: Authors' values, based on reconciliation of published data).**

	units	very low	low	medium	high	very high
pH H_2O[1]		<4.5	4.5-5.2	5.3-6.5	6.6-7.5	>7.5
Total N	%	<0.10	0.10-0.19	0.20-0.49	0.50-1.00	>1.00
Organic C	%	<2.0	2.0-3.9	4.0-9.9	10.0-20.0	>20.0
Exch. K	cmol/kg	<0.10	0.10-0.19	0.20-0.59	0.60-1.20	>1.20
Exch. Ca	cmol/kg	<2.0	2.0-4.9	5.0-9.9	10.0-20.0	>20.0
Exch. Mg	cmol/kg	<0.3	0.3-0.5	0.6-0.9	1.0-6.0	>6.0
Exch. Na	cmol/kg	<0.10	0.10-0.29	0.30-0.69	0.70-2.00	>2.00
CEC	cmol/kg	<5	5-10	11-25	>25	-
ECEC	cmol/kg	<2	2-5	6-10	11-20	>20
Base Satn.	%	<10	10-19	20-60	>60	-
Al Satn.	%	<20	20-39	40-59	60-80	>80[3]
Avail P.	µg/ml	<10	10-19	20-30	>30	-
P retn.	%	<10	10-59	60-84	85-95	>95
Reserve K[4]	cmol/kg	<0.10	0.10-0.19	0.20-0.34	0.35-0.50	>0.50
Reserve Mg[5]	cmol/kg	<3.0	3.0-6.9	7.0-14.9	15.0-30.0	>30.0
Soluble B[6]	µg/g	<0.50	0.50-0.99	1.00-1.99	2.00-5.00	>5.00
Sulphate-S[7]	µg/g	<5	5-14	15-49	50-150	>150
DTPA[9] Fe	mg/kg	<4.5				-
DTPA[9] Mn	mg/kg	<3.0				>140[8]
DTPA[9] Cu	mg/kg	<0.6				>11[8]
DTPA[9] Zn	mg/kg	<0.5				>7[8]

[1] Soil:water ratio of 1:5
[2] Exch. K should also represent at least 3% of total exchangeable bases
[3] Al saturation greater than 80% is toxic to coffee.
[4] Extracted in boiling nitric acid.
[5] Extracted in boiling 1M hydrochloric acid.
[6] Determined in hot water extract.
[7] Extracted with 0.04M calcium phosphate and the sulphur extract measured turbidimetrically following treatment with charcoal and an acid digestion to remove organic matter.
[8] Trace element contents in excess of these values may be toxic.
[9] Determined in diethylene triamine pentacetic acid using the method of Lindsay and Norvell (1978). Figures are only tentative.

tation (SPN 1.02), application of sulphate of ammonia produced a pronounced negative effect on topsoil pH, which decreased with increasing applications of nitrogen, up to 400 kg N/ha/y. At this application rate topsoil pH decreased from 5.2 to 4.3 over four years (Table 2). The acidification effect was recorded to depths of at least 60 cm below the soil surface (Table 3). Nitrogen did not produce a significant negative effect on topsoil exchangeable potassium levels (Table 2), although leaching of potassium down the soil profile occurred because of the soil acidification (Table 3). Similarly, nitrogen applications induced leaching of magnesium and calcium down the soil profile, much of the magnesium and calcium being leached below 60 cm from the surface (Table 3). Harding (1993 c) also reported significant negative nitrogen effects on topsoil exchangeable magnesium and calcium contents (Table 2).

Potassium applications resulted in a significant positive effect on topsoil exchangeable potassium levels (Table 4), but also tended to have a negative effect on topsoil exchangeable magnesium and calcium levels (Harding 1993 c). Applications of phosphorus fertiliser produced a significant positive effect on topsoil available phosphorus levels. When these effects are compared with those from an

Table 2. **Nitrogen fertiliser effects on topsoil properties after four years of nitrogen applications (data from 1991).**

kg N/ha/y	Number of plots	pH			Total N(%)			Exchangeable cations (cmol/kg) K			Mg			Ca		
		KS[1]	KU[1]	AU[1]	KS	KU	AU	KS	KU	AU	KS	KU	AU	KS	KU	AU
100	12	5.0	4.8	4.8	0.96	0.77	0.54	0.37	0.49	0.63	0.40	0.45	1.01	2.0	1.6	3.5
200	12	4.7	4.5	4.6	0.91	0.80	0.62	0.32	0.39	0.40	0.26	0.30	0.80	1.3	1.2	3.3
300	12	4.4	4.3	4.4	0.95	0.79	0.55	0.33	0.42	0.42	0.13	0.21	0.54	0.7	0.8	2.2
400	12	4.3	4.2	4.1	0.88	0.78	0.55	0.35	0.41	0.36	0.11	0.16	0.35	0.4	0.5	1.3
F-prob.[2]		***	**	**	ns	ns	ns	ns	**	ns	***	**	**	***	**	**
S.E.D.[3]		0.04	0.05	0.10	0.04	0.022	0.020	0.020	0.016	0.099	0.040	0.043	0.137	0.20	0.18	0.50

[1] KS = Koban Plantation shaded coffee; KU = Koban Plantation unshaded coffee; AU = Aiyura HAES unshaded coffee.
[2] ns = not significant; * = significant at 5% level; ** = significant at 1% level; *** = significant at 0.1%
[3] Standard error of the means (16 *df*)

Table 3. **Nitrogen and potassium fertiliser effects on pH and exchangeable cations at four depths under coffee at Koban Plantation and Aiyura HAES (1991 data).**

		N=0, K_2O=0 kg/ha/y				N=100, K_2O=400 kg/ha/y				N=400, K_2O=400 kg/ha/y			
	Depth		ex. Cations (cmol/kg)				ex. cations (cmol/kg)				ex. cations (cmol/kg)		
Location	(cm)	pH	K	Mg	Ca	pH	K	Mg	Ca	pH	K	Mg	Ca
Koban shaded	0-15	5.7	0.23	1.20	6.1	4.6	0.65	0.18	0.5	4.2	0.57	0.08	0.6
	15-30	5.6	0.17	0.71	3.1	5.2	0.32	0.49	2.9	5.1	0.81	0.34	4.9
	30-45	5.7	1.04	1.28	3.3	5.2	0.40	1.48	4.9	5.0	0.64	1.81	6.2
	45-60	5.4	0.90	0.96	3.8	5.2	0.13	1.51	4.6	5.1	0.36	2.23	5.7
Koban unshaded	0-15	5.0	0.24	0.23	0.8	4.8	0.70	0.49	1.6	4.2	0.64	0.14	0.3
	15-30	5.2	0.17	0.27	1.7	5.2	0.38	0.83	2.8	4.5	0.42	0.17	0.8
	30-45	5.3	0.26	0.73	3.6	5.1	0.75	2.50	5.8	4.9	0.47	1.47	5.3
	45-60	5.1	0.21	0.87	3.4	5.0	0.67	2.15	4.8	4.9	0.51	1.93	5.0
Aiyura unshaded	0-15	5.3	0.23	1.34	4.8	4.8	1.99	0.56	3.3	4.1	0.63	0.22	0.4
	15-30	5.0	0.12	1.02	2.5	4.9	0.58	1.35	4.1	4.3	0.59	0.31	1.3
	30-45	5.2	0.15	1.39	2.4	4.9	0.44	1.77	4.2	4.7	0.31	0.78	2.0
	45-60	5.1	0.19	2.41	2.4	4.9	0.13	1.51	3.0	4.9	0.36	2.69	5.1

[1] Soil properties measured in September 1991 after four years of fertiliser applications.

Table 4. **Potassium fertiliser effects on topsoil properties after four years of potassium applications.**

kg K_2O/ha/y	Number of plots	Exch. K (cmol/kg)			Exch. Mg (cmol/kg)			Exch. Ca (cmol/kg)		
		KS[1]	KU[1]	AU[1]	KS	KU	AU	KS	KU	AU
0	16	0.19	0.23	0.17	0.26	0.32	0.65	1.3	1.2	2.7
200	16	0.36	0.44	0.38	0.25	0.28	0.75	1.1	1.1	2.7
400	16	0.48	0.61	0.81	0.17	0.23	0.62	0.9	0.8	2.4
F-Prob.[2]		***	**	**	ns	**	ns	ns	**	ns
SEM[3]		0.020	0.014	0.086	0.030	0.037	0.18	0.16	0.18	0.43

[1] KS = Koban Plantation shaded coffee; KU = Koban Plantation unshaded coffee; AU = Aiyura HAES unshaded coffee
[2] ns = not significant; * = significant at 5% level; ** = significant at 1% level; *** = significant at 0.1% level
[3] Standard error of the means (16 *df*)

adjacent unshaded trial, it would appear that the shade trees have a moderating effect on soil acidification, but reduced topsoil exchangeable potassium and magnesium contents more rapidly.

Unshaded coffee

In fertiliser trials under unshaded coffee on Aiyura and Koban Plantation (SPN 1.03 and 1.01), Harding (1992 a and 1993 b) reported that application of the nitrogenous fertiliser (sulphate of ammonia, SoA) produced a pronounced negative effect on topsoil pH, which decreased with increasing applications of nitrogen, up to 400 kg N/ha/y (Table 2). The acidification effect was recorded to depths of at least 60 cm below the soil surface (Table 3). Nitrogen also produced a highly significant negative effect on topsoil exchangeable potassium levels (Table 2), due to leaching of potassium down the soil profile because of the nitrogen induced soil acidification. Similarly, nitrogen applications induced leaching of magnesium and calcium down the soil profile (Table 3), much of the magnesium and calcium being leached below 60 cm from the surface. Application of potassium produced a highly significant positive effect on topsoil exchangeable potassium levels (Table 4). On Koban Plantation, those plots receiving no potassium fertiliser, topsoil exchangeable potassium contents decreased from a mean of 0.79 cmol/kg to only 0.23 cmol/kg over a four year period - that is from a high level to the lower end of the medium range (Table 1). Applications of 400 kg K_2O/ha/year were sufficient to maintain high levels of topsoil exchangeable potassium. Potassium also tended to have a negative effect on topsoil exchangeable magnesium and calcium levels (Table 4), although the effect was not always statistically significant.

A highly significant nitrogen x potassium interaction effect was also recorded in the topsoil exchangeable potassium contents, which increased most at low nitrogen and high potassium application rates (Harding 1993 b). Phosphorus and magnesium applications produced no significant effects on the soil, although topsoil available phosphorus and exchangeable magnesium levels respectively were increased.

LEAF NUTRIENT CONTENT STUDIES

Hart and Southern (1969) were the first in PNG to consider the most appropriate methods for collecting coffee leaf samples and analysing them in the laboratory. Southern (1966) and Hart (1969) provided early guidelines for interpreting the analytical results from coffee leaf analyses. Building on the pioneering work of Southern and Hart, and utilising results from other parts of the world, Harding (1986) compiled comprehensive guidelines on collecting and preparing coffee leaf samples, analytical methods, and interpretation of the analytical results (Table 5).

Table 5. **Critical levels of nutrients in arabica coffee leaves (Willson 1985).**

nutrient	unit	deficient	subnormal	normal	excess
N	%	<2	2.00-2.60	2.61-3.50	<3.5
P	%	<0.10	0.10-0.15	0.16-0.20	>0.20
K	%	<1.50	1.50-2.00	2.11-2.60	>2.60
Ca	%	<0.40	0.40-0.75	0.76-1.50	>1.50
Mg	%	<0.10	0.10-0.25	0.26-0.40	>0.40
S	%	<0.10	0.10-0.15	0.16-0.25	>0.25
Fe	mg/kg	<40	40-70	71-200	>200
Mn	mg/kg	<25	25-50	51-100	>100
Zn	mg/kg	<10	10-15	16-30	>30
Cu	mg/kg	<3	3-7	8-20	>20
B	mg/kg	<25	25-40	41-90	>90
Al	mg/kg				>60
Mo	mg/kg	<0.5	0.5-0.8		

Table 6. **Effects of nitrogen and potassium applications on leaf nutrient contents[1] in smallholder coffee gardens, 1991.**

kg N/ha/y	number of plots	N (%)	Mn (mg/kg)	Cu (mg/kg)
0 N	48	2.6	157	15
50 N	48	2.7	186	13
100 N	48	2.8	237	13
F-prob.[2]		**	**	**
SEM[3]		0.02	9.1	0.4
Kg K_2O/ha/y		K (%)	Mg (%)	B (mg/kg)
0 K_2O	48	1.5	0.5	33
50 K_2O	48	1.6	0.5	30
100 K_2O	48	1.8	0.4	29
F-prob[2]		**	**	**
SEM[3]		0.1	0.1	1.0

[1] Leaf nutrient contents in June 1991, after four years of fertiliser applications.

[2] ns = not significant; ** = significant at 1% level.

[3] Standard error of the means

Seasonal fluctuations

Southern (1969) was the first in PNG to show the existence of seasonal fluctuations in the nutrient contents of coffee leaves. His studies of research station trials extended over a period of almost three years, but unfortunately, it was not possible to collect leaf samples consistently throughout this period. More recently, three studies of coffee leaf nutrient contents were conducted over a three year period (1987 to 1990), with monthly sampling throughout the period. These studies involved twenty unfertilised smallholder coffee gardens in the Eastern Highlands (SPN 8.02) (Harding 1991 a); seven fertilised coffee blocks on Aiyura HAES (SPN 8.01); and six fertilised plantation blocks in the Western Highlands (SPN 8.03) (Harding 1991 b).

These studies clearly demonstrated that coffee leaf nutrient contents exhibit, often very pronounced, seasonal fluctuations. These fluctuations, which are not the same for all nutrients, can be related to the annual development cycle of the coffee, and the annual rainfall distribution pattern (Harding 1993 a). They are therefore relatively predictable. Meaningful interpretation of leaf analytical data is therefore only possible if the date of leaf sample collection is known, and the seasonal fluctuations in leaf nutrient contents are understood.

These studies greatly facilitate such interpretations. The studies also showed that fertiliser applications produced surprisingly little effect on the seasonal fluctuations of leaf nutrient contents, although leaf nutrient levels *per se* were increased by fertiliser applications. The seasonal fluctuations in leaf nutrient contents also provide some indications as to when particular nutrients are in shortest supply, and therefore likely to be most efficiently utilised if applied as fertiliser. This has recently been confirmed in a fertiliser timing trial (SPN 1.04) on Ondu Plantation (Hombunaka and Harding 1994).

Leaf nutrient content responses to fertiliser applications - Shaded coffee

A fertiliser trial under smallholder coffee in the Eastern Highlands (SPN 2.01) showed a significant leaf N response to applications of N, during the first five year production cycle, although this was not agronomically important since all leaf N levels were already in the normal range (Harding 1994). N applications also resulted in a significant, positive effect on leaf manganese contents, and a negative effect on leaf copper contents (Table 6). Similarly, potassium applications produced a significant, positive effect on leaf K contents, and negative effects on leaf magnesium and boron contents (Table 6).

Southern (1969) reported little or no effect on leaf nitrogen levels when nitrogen was applied to shaded plantation coffee at Goroka (ACA 21) or on Korn Farm (ACA 25). Leaf nitrogen did increase in a trial on Aiyura HAES (ACA 7), but only if severe potassium deficiency also existed. Harding (1993 c) reported a significant positive effect on leaf nitrogen contents, when nitrogenous fertiliser was applied to the Koban shaded trial (SPN 1.02), but since nitrogen contents were all in the upper part of the normal range, this was of little agronomic significance (Table 7).

Potassium applications increased leaf potassium levels at Korn Farm, even at 75 kg K_2O/ha, but there was little additional response above 225 kg K_2O/ha. At Aiyura, leaf potassium levels were increased by application of 225 kg K_2O/ha, but still did not reach the normal range (Southern 1969). On Koban Plantation, Harding (1993 a) showed that applications up to 200 kg K_20/ha/y produced a significant positive response in leaf potassium contents after only eight months of commencing fertiliser treatments (Table 8). Southern (1969) reported no consistent phosphorus effects. Harding (1993 c) also reported that applications of 50 kg P_2O_5/ha/y did not affect leaf phosphorus contents, which remained at adequate levels throughout the trial period. Magnesium, at a rate of 50 kg MgO/ha/y, produced a positive effect on leaf magnesium contents, although the effect was not significant until the fourth year of applications.

Indirect nutrient effects recorded in these trials include a negative N-K effect (Southern 1969); a negative N-Ca effect (Harding 1993 c); a positive N-Mn effect when sulphate of ammonia was the nitrogen fertiliser (Southern 1969 and Harding 1993 c); negative N-P and N-B effects (Harding 1993 c); a negative K-Mg effect (Southern 1969 and Harding 1993 c); a positive K-Zn effect; a positive P-Mn effect; and a negative Mg-Ca effect (Harding 1993 c). Several of these effects are illustrated in Tables 7 and 8.

Table 7. **Effects of nitrogen applications on leaf nutrient levels[1] of coffee at Koban Plantation and Aiyura HAES.**

kg N/ha/y	Number of plots	N (%)			K (%			Mn (mg/kg)			B (mg/kg)		
		KS[2]	KU[2]	AU[2]	KS	KU	AU	KS	KU	AU	KS	KU	AU
100	12	3.1	3.0	2.7	2.5	2.3	1.5	489	424	331	48	43	46
200	12	3.1	3.1	2.9	2.5	2.3	1.5	489	424	331	48	43	46
300	12	3.2	3.1	3.1	2.6	2.2	1.5	539	441	386	43	40	44
400	12	3.1	3.1	3.0	2.6	2.4	1.5	471	429	357	46	40	43
F-prob.[3]		ns	**	**	ns	*	ns	*	**	**	***	**	**
SEM[4]		0.10	0.03	0.05	0.10	0.08	0.09	25	15	35	2.0	1.0	2.2

[1] Leaf nutrient contents in June 1991, after four years of fertilizer applications.
[2] KS = Koban Plantation shaded coffee; KU = Koban Plantation unshaded coffee; AU = Aiyura HAES unshaded coffee
[3] ns = not significant; * = significant at 5% level; ** = significant at 1% level; *** = significant at 0.1% level
[4] Standard error of the means (16 *df*)

Table 8. **Effects of potassium applications on leaf nutrient levels[1] of coffee at Koban Plantation and Aiyura HAES.**

kg K_2O/ha/y	Number of plot	K (%)			Mg (%)			Ca (%)		
		KS[2]	KU[2]	AU[2]	KS	KU	AU	KS	KU	AU
0	16	1.7	1.7	1.0	0.58	0.48	0.75	1.22	1.06	1.23
200	16	2.9	2.5	1.7	0.37	0.33	0.42	1.20	1.01	1.23
400	16	3.0	2.6	1.8	0.32	0.31	0.39	1.17	0.99	1.28
F-prob.[3]		***	**	**	***	**	**	ns	*	ns
SEM[4]		0.10	0.05	0.08	0.02	0.01	0.03	0.03	0.02	ns

[1] Leaf nutrient contents in June 1991, after four years of treatment applications.
[2] KS = Koban Plantation shaded coffee; KU = Koban Plantation unshaded coffee; AU = Aiyura HAES unshaded coffee.
[3] ns = not significant; * = significant at 5% level; ** = significant at 1% level; *** = significant at 0.1% level
[4] Standard error of the means (16 *df*)

When the fertiliser treatment effects on the leaf nutrient contents are compared with those recorded by Harding (1993 b) in an adjacent unshaded trial, several differences are apparent. In the shaded trial, leaf contents of phosphorus, magnesium, calcium, sulphur, zinc, boron, iron and manganese were generally higher than in the unshaded trial; and a positive potassium effect on leaf potassium levels became significant sooner in the shaded trial.

Leaf nutrient content responses to fertiliser applications - Unshaded coffee

In unshaded plantation coffee increases in leaf nitrogen contents following application of nitrogen fertilisers have been recorded by Southern (1969), and Harding (1992 a and 1993 b) (Table 7). These can occur very rapidly, sometimes being observed within 8 months. Leaf potassium contents have been shown to increase as a result of applications of potassium fertiliser (Table 8), the effect sometimes being observed within 14 months. Responses to phosphorus, however, are less clear, with increases in leaf phosphorus contents being recorded after three years. Magnesium applications of 50 kg MgO/ha/y produced a positive response in leaf magnesium contents after 20 months.

In addition to the direct responses in the leaf nutrient contents to fertiliser applications, many indirect effects have also been recorded. Such effects may be synergistic or antagonistic, and are sometimes of greater significance than the direct response. Indirect effects of nitrogen fertilisers include decreases in leaf calcium and boron (Harding 1992 a and 1993 b); a decrease in leaf sulphur (Southern 1969); a decrease in leaf phosphorus (Harding 1992 a); and an increase in leaf manganese levels (Southern 1969 and Harding 1992 a and 1993 b). Several indirect effects of nitrogen are illustrated in Table 7.

Indirect effects of potassium fertiliser include a decrease in leaf nitrogen (Southern 1969); a decrease in leaf magnesium (Southern 1969; Harding 1992 a and 1993 b); a decrease in leaf boron (Harding 1992 a and 1993 b); decreases in leaf phosphorus and sulphur (Harding 1992 a); a decrease in leaf

***Table 9.* Effects of organic and inorganic phosphorus sources on the growth of coffee polypot nursery seedlings after twelve months.**

Treatments	Dry matter production[1], Plant P[2], and total P uptake[3] per seedling				
	Shoots dry matter (g)	Roots dry matter (g)	Total dry matter (g)	Plant P (%)	Total P uptake (g)
With coffee skins	8.27	4.86	13.12	0.24	0.033
Without coffee skins	6.23	4.09	10.32	0.24	0.026
F-prob.[4]	**	**	**	ns	-
SEM[5]	0.162	0.132	0.274	0.006	-
No fertiliser	5.52	3.94	9.46	0.26	0.026
Rock phosphate	7.06	4.13	11.19	0.22	0.026
Triple superphosphate	7.89	4.93	12.81	0.25	0.034
Single superphosphate	8.53	4.90	13.43	0.24	0.034
F-prob.[4]	**	**	**	*	-
SEM[5]	0.227	0.188	0.389	0.008	-

[1] Dry matters refer to average 105°C oven dry weight.
[2] Plant P is %P on a 6°C oven dry basis.
[3] Total P uptake calculated from plant P (%) corrected to a 105°C oven dry basis.
[4] ns = not significant; * = significant at 5% level; ** = significant at 1% level.
[5] Standard error of the means (14 *df*)

calcium, and an increase in leaf manganese levels (Harding 1993 b). Several indirect effects of potassium are illustrated in Table 8

COFFEE NURSERY FERTILIZER STUDIES

A coffee polypot nursery trial at Aiyura (SPN 3.02), in which soil with a medium to low level of available P (12 mg/kg by the Olsen bicarbonate extraction), and a high P-retention capacity (91% by the method of Blakemore *et al.* 1981), was used in the potting mixture, produced significant, positive responses in plant growth to applications of organic, and inorganic, phosphorus (Harding 1988). After twelve months, the total dry matter production of the coffee seedlings was 27% higher with coffee skins incorporated in the potting mixture, than without coffee skins (Table 9). The coffee skins provided 0.18 g P and 3.23 g N/seedling.

Significant, positive responses to inorganic fertilisers, each providing 0.30 g P/seedling, were also recorded (Table 9). Total dry matter production after twelve months was 18% greater with Christmas Island Rock Phosphate, 35% greater with triple super phosphate (TSP), and 42% greater with single super phosphate (SSP), than with no fertiliser. Plant P levels did not reflect dry matter production, but total plant uptake did (Table 9). Table 10 summarises the relative benefits of incorporating coffee skins, and/or SSP in the potting mixture. Incorporating coffee skins and SSP resulted in a 75% increase in dry matter production.

A follow up observation trial (SPN 4.01) was established on Aiyura in March 1987, in order to monitor any residual effects of the nursery fertiliser treatments, particularly with regard to the slower release of P from the rock phosphate treatments. Nine coffee seedlings from each nursery trial treatment were planted in the field, and their development measured for a further two years. No clear residual effects from the nursery treatments were recorded (Harding 1992 b).

COFFEE PLANTING HOLE STUDIES

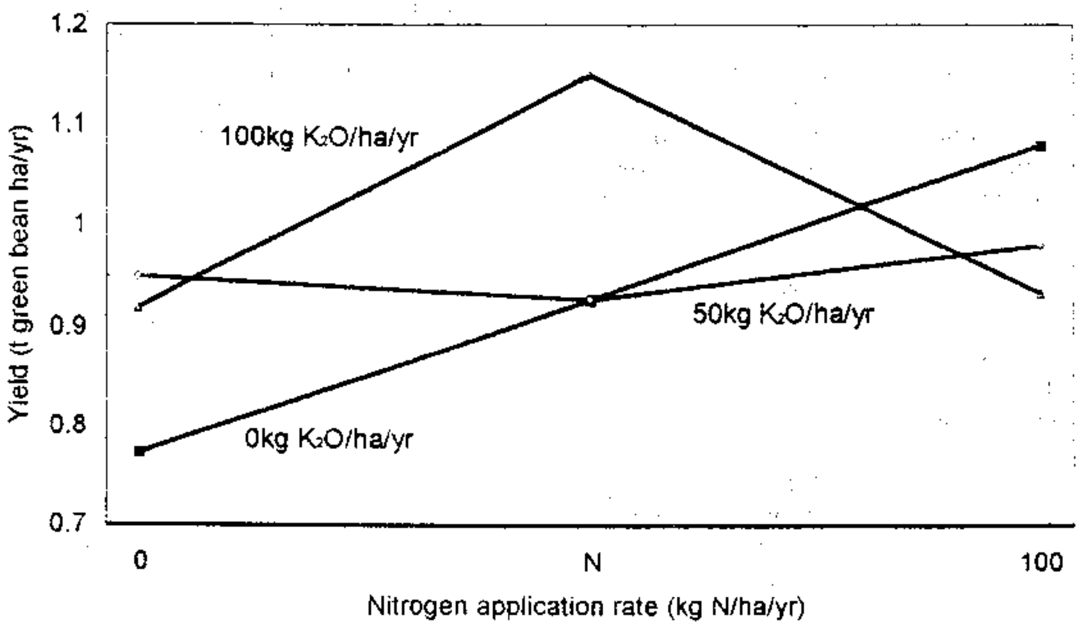
In March 1987, a planting hole trial (SPN 4.02) was established at Aiyura to investigate the optimum amount of phosphorus as TSP, to be applied to the planting hole when transplanting coffee seedlings from the nursery to the field. A location with a relatively high P-retention capacity was used, and the P treatments consisted of 0, 15, 30, 45, 60 and 75 g TSP per planting hole. All other recommendations were followed, including filling the holes with a 1:4 mixture of well rotted coffee skins and topsoil (to which was added the TSP), and timely applications of recommended amounts of nitrogen, potassium and micronutrients (Harding 1988). The results, although not statistically significant, suggested that 60 g TSP per planting hole resulted in the greatest dry matter accumulation.

A similar trial (SPN 4.03), using Catimor coffee seedlings, was established in January 1990 at the Western Highlands Substation. Treatments consisted of 0, 30, 60, 90, 120 and 150 g TSP per planting hole, with and without coffee pulp. Significant negative effects on soil and leaf zinc contents, and on growth parameters, were recorded, due to the high initial fertility of the peat soil used (Hombunaka 1997). The first crop (1990-1991) showed a negative yield response but in subsequent seasons there was no effect of the P application. Also the coffee pulp treatments yielded significantly lower between 1991 and 1993 but thereafter there was no yield effect.

***Table 10.* Effects of coffee skins and single superphosphate (SSP) on the growth of coffee polypot nursery seedlings after twelve months.**

Treatments	Total dry matter per seedling (g)	Plant P (%)	Total P uptake per seedling (g)
Soil only	8.70	0.25	0.023
Soil + coffee skins	10.22	0.27	0.029
Soil + SSP	11.84	0.24	0.030
Soil + SSP + coffee skins	15.02	0.24	0.038

Figure 1. **Yield response of rehabilitated, smallholder coffee to application of nitrogen and potassium.**



YIELD RESPONSES TO FERTILIZERS

Shaded coffee

A number of facts point to likely time lags in coffee yield responses to fertiliser applications, as reviewed in Harding (1994). These include the need for fertiliser applications to first affect shoot growth, the number of primaries per tree, flowers per cluster, and the precocity of flowering nodes, all of which subsequently determine the coffee cherry yield.

In the PNG context, the likely major effects of shade trees on coffee are to reduce yields, biennial bearing, overbearing and dieback; reduce the demands for nutrients; and thus reduce yield responses to fertiliser applications. Thus, yield responses to fertiliser applications in traditional smallholder coffee gardens are very unlikely. The only fertiliser trial conducted in improved smallholder coffee gardens (SPN 2.01) commenced in 1986 and was terminated in 1997. The trial originally consisted of a 3x3 factorial design, with one replicate located in each of twenty rehabilitated smallholder coffee gardens in the Kainantu area of Eastern Highlands Province. Three nitrogen treatments (0, 50 and 100 kg N/ha/y as sulphate of ammonia) and three potassium treatments (0, 50 and 100 kg K_2O/ha/y as muriate of potash) were applied in four equal doses in October, December, February and April each year. In addition to the nine rehabilitated plots, each garden also contained an unfertilised, unrehabilitated, external control plot, located in adjacent unrehabilitated coffee. The results from the first five year cycle have been reported in Harding (1988) and Harding (1994).

The yields from the trial are of interest because they are based on the only directly recorded long-term smallholder coffee yields in PNG. The average yield of all rehabilitated plots over the first five year production cycle was 1112 kg green bean/ha/y. However, the mean yields from individual gardens varied greatly, from as low as 100 to as high as 3300 kg green bean/ha/y. Yields also varied from year to year, with the lowest yields being recorded in the first year following rehabilitation, but then increasing each year to peak in the fourth year of the production cycle (when allowances are made for unusual weather conditions). When the yields from the unrehabilitated external control plots were compared with the unfertilised, but rehabilitated, plots in each garden, the rehabilitation alone was shown to have significantly increased cumulative yields over the first five year cycle by 46% (Harding 1994).

Significant fertiliser effects on coffee yields were also recorded during the first production cycle. When all the coffee gardens are analysed together, a significant positive nitrogen effect was recorded during the final year of the cycle, with yields peaking at a little above 50 kg N/ha/y. A potassium effect was also recorded, with yields increasing up to at least 100 kg K_2O/ha/y, although the response was not statistically significant. A significant NxK interaction was also apparent, highest yields being obtained when 100kg K_2O/ha/y and 50kg N/ha/y were applied (Figure 1).

When different groupings of gardens are analysed together, significant positive nitrogen and potassium effects on coffee yields are apparent during the fourth and fifth years in the less fertile gardens. Harding (1994) has shown by modelling the N dynamics of smallholder coffee gardens, that the efficiency of the shade trees in biologically fixing nitrogen from the atmosphere is likely to be a key factor in the response of individual coffee gardens to applications of nitrogenous fertilisers. The second production cycle commenced in 1991, utilising eight selected gardens from the first cycle. Similar trends to those during the first cycle have been recorded (Hombunaka unpublished data).

Much of the early coffee nutrition research was conducted in shaded plantation coffee. A positive yield response to nitrogen applications up to 256 kg N/ha/y was reported from a shaded coffee trial (ACA 25) on Korn Farm, in the Western Highlands. However, ten years were required before a statistically significant yield response was recorded (DASF 1972). The majority of fertiliser trials under shaded plantation conditions however, have either shown no response to nitrogen, or shown a negative response. Thus early fertiliser trials (ACA 4 and ACA 28) on Aiyura showed no response to applications of nitrogen (DASF 1965 b and 1966). Trial ACA 7 on Aiyura was reported as having a negative response to N applications by DASF (1965 b), and later Byrne (1984) reported a similar response for the period 1962-70 (Figure 2). A fertiliser trial (ACA 21) at Goroka also showed a negative response to N (DASF 1968). More recently, a five year factorial fertiliser trial (SPN 1.02) in lightly shaded coffee on Koban plantation, in the Western Highlands, showed a negative response to N applications above 100 kg N/ha/y, despite yields averaging 1972 kg green bean/ha/y over the five year cycle (Harding 1993 c). Green bean yields in this trial were 22.7% lower than in an adjacent unshaded trial.

***Table 11.* Micronutrient application effects on coffee yield (kg green beans/ha/y)**

	1992/93	1993/94	1994/95	1995/96	1996/97
no fertilizer	3172	2555	2508	2316	1088
no micronutrients	3662	2562	4895	2386	2428
foliar Zn	4438	3660	5297	2571	2702
foliar B	3070	4225	4027	2505	2012
foliar Zn + B	3919	3938	4876	2809	2326
soil Zn	3973	4312	4765	2698	2568
soil B	4076	3971	4400	2121	2628
soil Zn + B	2965	3658	4089	2310	2037
F prob.[1]	*	ns	**	ns	ns
SEM[2]	142	176	204	99	166

[1] ns = not significant; * = significant at 5% level; ** = significant at 1% level.

[2] Standard error of the means (21 *df*)

Figure 2. **Yield responses of shaded and unshaded plantation coffee to applications of nitrogen.**

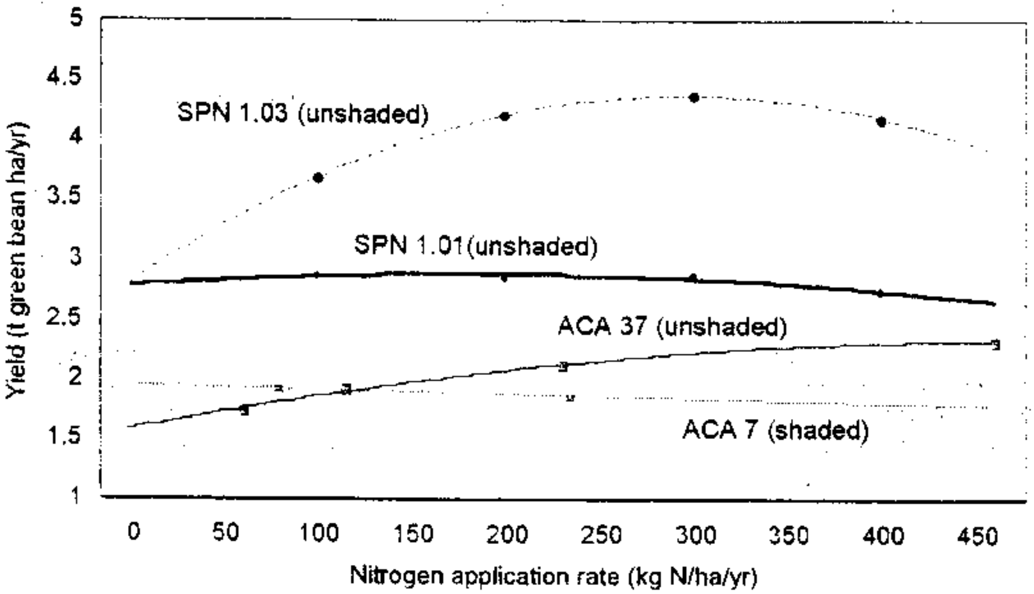
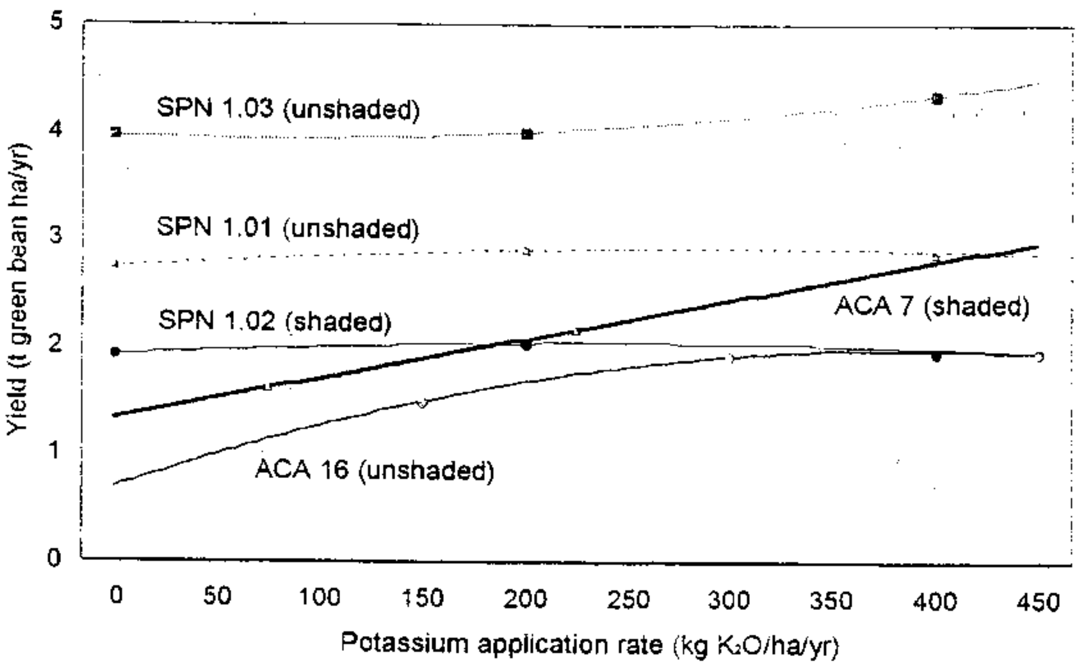


Figure 3. **Yield responses of shaded and unshaded plantation coffee to applications of potassium.**



In shaded coffee potassium is often the most limiting nutrient (Southern 1969) due to the plentiful supplies of nitrogen which are typically available under shaded conditions. Many authors have therefore reported positive yield responses to potassium, for example DASF (1965 b) and Byrne (1984) on Aiyura (ACA 7); DASF (1966, 1968, 1972) on Korn Farm (ACA 25); and Harding (1993 c) on Koban Plantation (SPN 1.02) (Figure 3). Application rates at which yield responses have been achieved have been rather high, such as 225 kg K_2O/ha/y (DASF 1965 b, 1966, 1968 and 1972); 300 kg K_2O/ha/y (Byrne 1984); and up to 400 kg K_2O/ha/y (Harding 1993 c). Considerable time may also be required before this response becomes apparent. Thus, trial ACA 7 first showed a significant potassium response during its fifth year (DASF 1965 b), and trial ACA 25 first recorded a significant response to potassium during its sixth year (DASF 1966). A few authors, for example DASF (1968) in trial ACA 21 at Goroka, have recorded a negative response to potassium, which suggests that the response of coffee to potassium is dependent on the soil type.

Yield responses to phosphorus in mature coffee are rare (Ling *et al.* 1990). In PNG, negative yield responses to phosphorus were recorded by DASF (1965 b), DASF (1972) and Byrne (1984) on Aiyura HAES (ACA 7); DASF (1968) at Goroka (ACA 21); and Harding (1993 c) on Koban Plantation (SPN 1.02). Indications of a positive response to phosphorus were reported for some years in trial ACA 25 on Korn Farm (DASF 1968). There are very few reports in the literature of coffee yield responses to applications of magnesium, although a non-significant positive yield response to 50 kg MgO/ha/y was apparent in trial SPN 1.02 on Koban Plantation (Harding 1993 c).

The importance of adequate micronutrient applications, particularly following a change in production cycle when new suckers are growing, has been demonstrated by Hombunaka (1997). Significant yield responses to zinc and boron were recorded during several years of a trial (SPN 4.06) under shaded coffee at Aiyura HAES. Zinc is most effectively applied as a foliar spray, while boron is best applied to the soil.

Unshaded coffee

Coffee yields respond more often to nitrogen than any other nutrient, particularly when grown under unshaded conditions. Many authors have reported positive yield responses to applications of nitrogen in PNG. An unshaded fertiliser trial on Aiyura HAES (ACA 37) showed a consistent positive yield response over seven years (1970-77) to annual applications of nitrogen up to 460 kg N/ha (Byrne 1984) (Figure 2); and on Korn Farm (ACA 25) a significant yield response to nitrogen was recorded in 1967-69 (DASF 1972).

More recently, Harding (1992a) reported that unshaded coffee on Aiyura HAES (SPN 1.03) responded positively to applications of up to 330 kg N/ha/y (as sulphate of ammonia) from the third year of treatment applications (Figure 2). The yields from this trial averaged a very high 4654 kg green bean/ha/y during the first five year production cycle. During its second five year cycle, nitrogen was applied as calcium ammonium nitrate (CAN). Yields continued to respond positively to nitrogen, and averaged more than 3000 kg green bean/ha/y (Hombunaka unpublished data). An unshaded trial on Koban Plantation (SPN 1.01) also showed a small positive response to N (Figure 2), with yields peaking at an application rate of 200 kg N/ha/y (Harding 1993 b). High fertiliser applications prior to the commencement of this trial reduced yield responses during the trial. Yields in this trial averaged 2551 kg green bean/ha/y during the five year production cycle.

Only rarely does unshaded coffee fail to respond to nitrogen. However, in unshaded trial ACA 16 on Aiyura HAES, a significant positive response to rates up to 104 kg N/ha/y was observed over the first six years (1963-69) (DASF 1972), but when rates were increased up to 460 kg N/ha/y, yields were depressed over the next five years (Byrne 1984). More recently, Hombunaka (1997) reported no response to N and K fertilisers (SPN 405) on peaty soils at the Western Highlands substation. Depending on the soil properties, unshaded coffee sometimes responds to applications of potassium. The only clear effect in an early nutrient omission trial (ACA 4) was in response to omitting potas-

Table 12. **Fertiliser timing effects on coffee yield (kg green beans/ha/y).**

fertiliser timing[1]	1992/93	1993/94	1994/95	1995/96
1	744	655	505	1523
2	1186	705	828	1574
3	1007	960	1438	2280
4	950	1030	1283	2153
5	785	890	1305	2216
6	970	896	11/5	2010
7	927	830	937	1949
8	1989	892	1285	2134
9	949	968	1531	2180
10	881	969	937	2284
F prob.[2]	*	**	ns	*
SEM[3]	35	26	78	64
kg N and kg K_2O/ha	**1992/93**	**1993/94**	**1994/95**	**1995/96**
100-100	930	760	918	1680
200-200	1010	926	1103	2080
300-300	1940	952	1352	2331
F prob.[2]	***	*	***	ns
SEM[3]	35	26	78	64

[1] the trial included 100, 200 and 300 kg N or K2O/ha/y given at different times for details see Hombunaka (1997).
[2] ns = not significant; * = significant at 5% level; ** = significant at 1% level; *** = significant at 0.1% level.
[3] standard error of the means (58 *df*).

sium DASF 1965 a); and a significant response was obtained in a trial on Korn Farm (ACA 25) to applications of 375 kg K_2O/ha/y (DASF 1972). Unshaded trial ACA 16 on Aiyura, responded positively to applications of potassium up to 450 kg K_2O/ha/y over the five year period 1971-76 (Byrne 1984) (Figure 3). However, trial ACA 37 on Aiyura failed to produce a yield response to annual applications of up to 900 kg K_2O/ha/y over a seven year period (1970-77) (Byrne 1984).

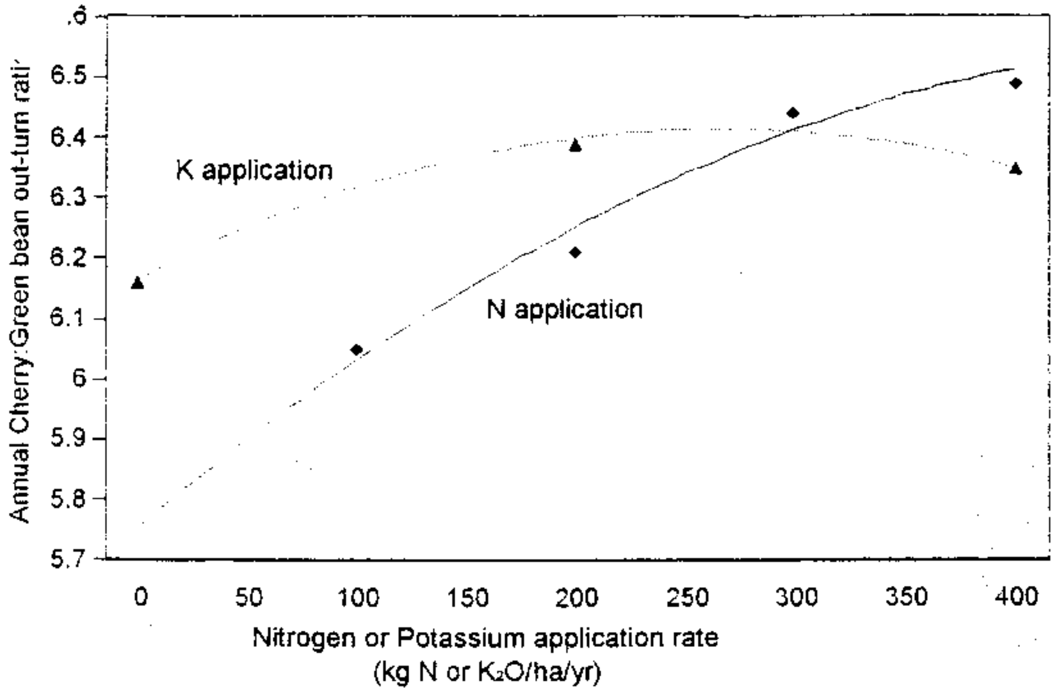
A significant positive yield response to potassium applications up to 200 kg_2O/ha/y was recorded in the unshaded Koban Plantation trial SPN 1.01 (Harding 1993 b); and Harding (1992 a) reported yields from an unshaded trial (SPN 1.03) on Aiyura responded positively, but not significantly, to applications up to 400 kg K_2O/ha/y during its first five year production cycle (Figure 3). During its second cycle, which begun in October 1991 a less acidifying N source (CAN) was used. It was found that in the second cycle yields were on average lower which could be due to Ca/K imbalances caused through the CAN application.

In PNG, no consistent, significant, positive yield response to phosphorus has been recorded. However, indications of a positive yield response to phosphorus were reported during some years in trials ACA 16 and SPN 1.03 on Aiyura (DASF 1972; Byrne 1984 and Harding 1992 a); and on Korn Farm (ACA 25) (DASF 1968). Negative yield responses to phosphorus have not been recorded in unshaded coffee trials in PNG. No significant yield responses to magnesium have been reported from unshaded coffee in PNG.

TIMING OF FERTILIZER APPLICATIONS

A fertiliser timing trial (SPN 1.04) was established on Ondu Plantation, in the Eastern Highlands Province, in 1988, in order to investigate the best time to apply nitrogen and potassium fertilisers. Taking

Figure 4. **Effects of applications of nitrogen and potassium on coffee cherry: green out-turn ratios, Aiyura HAES, 1990/91**



due account of the interpretation of fluctuations in coffee leaf nutrient contents described in a previous section, ten fertiliser timing schedules, and three application rates, were incorporated into the trial. The trial continued until mid-1997. Hombunaka (1997) reported significant responses to fertiliser timing and application rates for the 1992 to 1996 coffee seasons (Table 12). The trial demonstrated that nitrogen fertiliser is best applied soon after the rains begin (when flowering is triggered), during rapid cherry expansion, and just prior to the final ripening stage. Whereas potassium is required in two applications during rapid cherry expansion.

COFFEE OUT-TURN RATIO RESPONSES TO FERTILIZER APPLICATIONS

Harding (1992 a, 1993 b and 1993 c) has shown that as nitrogen applications increase, cherry : green bean out-turn ratios also increase significantly (Figure 4), that is, more pulp is produced relative to green bean. Potassium (Figure 4) and magnesium have also been shown to positively affect coffee out-turn ratios.

In a smallholder coffee fertiliser trial (SPN 2.01), no significant nutrient effect on out-turn ratios was recorded during the first production cycle (Harding 1994)

NUTRIENTS IN COFFEE WASTE PRODUCTS

Harding (1994) collected coffee prunings from six rehabilitated smallholder coffee plots receiving from 0 to 100 kg N and K_2O/ha/y, and three unshaded plantation plots receiving from 0 to 600 kg N and K_2O/ha/y, for two years. Dry matter (DM) and nutrient contents of each component of the prunings were determined, from which it was estimated that over a five year production cycle, smallholder coffee gardens produce between 10,000 and 32,000 kg DM of prunings/ha, containing 145 to 500 kg N, depending on the fertiliser applications. Unshaded coffee plantations were estimated to produce between 31,000 and 69,500 kg DM of prunings/ha over a five year cycle, containing 410 to 1300 kg N, the actual quantities being very influenced by fertiliser applications.

Although most coffee prunings are usually recycled, coffee stems are often removed for other purposes, such as fuel or fence construction. Willson (1985) presented data from PNG showing that the removal of only one stem per tree from coffee planted at 1350 trees/ha, represents a loss of 14.8 kg N, 2.8 kg P_2O_5 and 11.9 kg K_2O/ha. Hart (1969) reported the equivalent of 22.0 kg N, 4.6 kg P_2O_5, 20.4 kg K_2O and 3.3 kg MgO per 1000 kg green bean. Harding (1994) collected 5-10 kg samples of harvested ripe coffee cherries from nine rehabilitated smallholder coffee plots receiving from 0 to 100 kg N and K_2O/ha/y, and 14 kg samples from eight unshaded plantation plots receiving from 0 to 700 kg N and K_2O/ha/y, in 1991. Each sample was processed to the green bean stage, and the dry matter and nutrient contents of the green bean, pulp, mucilage, parchment and silverskins were determined. It was estimated that one tonne of fresh cherry from smallholder coffee gardens contains 200 kg dry matter and 4 kg N, about 50% in the green bean, 25% in the pulp, 10% in the mucilage, and 10% in the parchment and silverskins. One tonne of unshaded plantation cherry was estimated to contain 220 to 280 kg dry matter and 4 to 5 kg N, about 50% in the green bean, 25% in the pulp, 6% in the mucilage, and 15% in the parchment and silverskins. Fertiliser application rates significantly influenced dry matter and N contents of the unshaded plantation cherry (Harding 1994).

MODELLING COFFEE NUTRITION

Harding (1994) collected litterfall for a two year period (January 1991 to December 1992) from six rehabilitated smallholder coffee plots receiving from 0 to 100 kg N and K_2O/ha/y, and five unshaded plantation plots receiving from 0 to 600 kg N and K_2O/ha/y. Dry matter and nutrient contents of each component of the litterfall were determined, from which it was estimated that over a five year production cycle, smallholder coffee gardens produce 6,800-7,500 kg DM of coffee tree litter/ha, containing 170-250 kg N, and 34,400-40,700 kg DM of yar (shade) tree litter/ha, containing 460-600 kg N, depending on the fertiliser applications. Thus, total litterfall in smallholder coffee gardens over a five year production cycle was estimated to be 41,200-48,200 kg DM/ha, containing 637-761 kg N. Unshaded coffee plantations were estimated to produce 10,000-20,000 kg DM of litterfall/ha over a five year cycle, containing 188-456 kg N, the actual quantities being very influenced by fertiliser applications.

The litter, prunings and cherries taken together represent the above ground biomass production, if the growth of the woody material is ignored. If a typical average yield of 7 tonnes cherry/ha/y is assumed for the shaded coffee, the shaded coffee system produces 58,000-87,000 kg above ground biomass DM/ha, containing 900-1,400 kg N/ha, in a five year cycle. On an annual basis, this is 11,600-17,400 kg DM/ha, containing 180-280 kg N/ha, of which the harvested cherries account for about 10%. The above ground biomass production of the unshaded coffee, assuming an average yield of 29 tonnes cherry/ha/y, can be calculated in a similar way as 14,600-26,000 kg DM/ha/y, containing 240-500 kg N/ha/y. This is up to 50% more biomass, containing up to almost 80% more N, than the shaded coffee system. The harvested cherries account for a considerably larger 30% or more of the N contained in the above ground biomass production.

Harding (1994) modified the previously validated, empirical, N model of Wolf *et al.* (1989) to cater for the coffee management systems of PNG. Using coffee cherry, litterfall, prunings, stem and roots dry matter and nutrient contents, with soil and leaf analytical data, this PNG coffee N model was calibrated for PNG conditions. The model was then used to derive five year N balances which explained observed responses to N applications in shaded and unshaded coffee, and highlighted the crucial role played by the yar shade trees in smallholder coffee gardens. The PNG coffee N model was used to generate long-term (200 and 500 years) simulations of the N dynamics in selected plots of shaded and unshaded coffee fertiliser trials. These showed that in shaded coffee gardens where the N requirements of the coffee trees cannot be met from naturally occurring sources, the labile organic N (LON) and stable organic N (SON) pools are depleted, and N uptake (and hence yields) and N losses are reduced, until a new equilibrium is obtained. At this new steady state, the reduced N uptake and N losses are balanced by the N inputs from naturally occurring sources. Applications of N fertilisers in such gardens enables the LON and SON pools to equilibrate at higher levels, at which the potential N uptake, and hence coffee yields, are increased. In those gardens where the N requirements of the coffee are met by the naturally occurring sources, the LON and SON pools may, or may not, be depleted slightly. However, the new equilibrium occurs at such a level that the potential N uptake does not restrict the coffee yields (Harding 1994).

The long-term simulations also showed that in unfertilised, unshaded coffee, the LON and SON pools are so severely depleted, and the potential N uptake falls to such low levels, that the survival of the coffee trees as a commercial proposition is unlikely beyond a second production cycle. In high yielding (> 3000 kg green bean/ha/y) unshaded coffee receiving about 300 kg N/ha/y as fertiliser, the LON and SON pools may be depleted somewhat, but new steady state conditions are reached at a potential N uptake which is likely to be adequate for the survival of commercial coffee, although yields may fall somewhat. Applications of 600 kg N/ha/y would result in the LON and SON pools increasing to new equilibria, where potential N uptake is excessive and N losses are very high.

The long-term simulations of Harding (1994) were also used to investigate the consequences of three management options involving the recycling of waste products. These showed that unshaded, unfertilised coffee does not produce enough waste products to significantly affect the N balance, even if they were all recycled. In fertilised unshaded coffee, or in shaded coffee, however, the recycling of waste products, particularly the coffee pulp, does make a significant contribution to the N balance. As well as removing a major environmental pollutant, recycling waste products is likely to lead to reductions in N fertiliser requirements of up to 15 or 20%, and/or larger steady state LON and SON pools, and hence increased potential N uptake and coffee yields.

CONCLUSIONS

The seasonal fluctuations in coffee leaf nutrient contents are well understood, and guidelines for undertaking and interpreting coffee soil and leaf analyses have been established. Monitoring of coffee leaf nutrient contents can be a valuable aid to planning fertiliser requirements, providing seasonal fluctuations are understood. Coffee leaf nutrient contents can respond to applications of N or K within eight months. Responses to P and Mg are less likely and may take two or more years to become apparent. Considerable time lags, of two years or more, are usually required before coffee yield reponses to fertiliser applications. Similar delays may also occur before yield declines are apparent after reducing fertiliser applications. Fertiliser applications are utilised most efficiently when applied at the most appropriate times of year. Fertiliser timing studies have shown these to be at the flowering, rapid cherry expansion and final ripening stages for nitrogen, and during rapid cherry expansion for potassium. Nitrogen, K and Mg increase coffee cherry : green bean out-turn ratios, that is they produce more pulp relative to green bean. The beneficial effects of including well rotted coffee skins in coffee nursery potting mixtures, and planting holes in the field, have been demonstrated. Including up to 60 g TSP in each planting hole also results in improved growth and development of the coffee seedlings, except in very fertile soils, when negative effects on soil and plant zinc contents may occur reducing yields in the first cropping seasons.

Shaded coffee

Rehabilitation of smallholder coffee gardens can increase yields over a five year production cycle by almost 50%. Yields from rehabilitated smallholder coffee gardens can average as high as 3000 kg green bean/ha/y over a five year production cycle, although an average of 1000 kg green bean/ha/y is a more realistic target yield. Shaded plantation coffee yields can average 2000 kg green bean/ha/y over a five year production cycle. Field studies of shaded coffee show little evidence of N deficits. Leaf N contents, litterfall production, cherry partitioning, and out-turn ratios all show little or no positive response to N. The production of prunings does respond positively to N, and cherry and green bean yields respond positively in some shaded coffee but not in others. In some situations, applications of N result in a negative yield response. Most smallholder-shaded coffee in PNG could survive without applications of N fertiliser, although yields may decline to new equilibrium levels. Shaded plantation coffee is likely to require moderate applications of N fertiliser to maintain yields at commercial levels. Although shade appears to reduce the acidifying effect of N fertilisers, regular monitoring of soil pH should still be maintained. Responses to applications of potassium are likely in shaded coffee, since this is often the limiting nutrient under shaded conditions. Soil conditions may determine the extent of the yield response to potassium. Yield responses to P and Mg are rare in shaded coffee. The recycling of waste products, particularly the coffee pulp, can reduce the need for fertiliser N applications by up to 20%, and will increase potential yields in some coffee gardens. Coffee prunings contain significant amounts of nutrients, and should therefore be fully recycled if possible. The extent of biological N fixation by the "yar" trees is an important factor in determining the long-term sustainability of unfertilised shaded coffee.

Unshaded coffee

Unshaded plantation coffee in PNG can yield as high as 4000 kg green bean/ha/y over a five year production cycle, although average yields of 2500 or 3000 kg green bean/ha/y are more realistic target yields. Field studies of unshaded coffee provide strong evidence of the need for applications of both N and K. Leaf N contents, litterfall production, prunings production, cherry partitioning, outturn ratios, cherry and green bean yields all respond positively to applications of up to about 325 kg N/ha/y. No N fertiliser applications would probably result in the death of most trees within two production cycles. High rates of fertiliser N could lead to yield reductions if the trees produce too much foliage, at the expense of flowers. Soil acidification is a potential problem when acidifying N fertilisers like sulphate of ammonia are used and this may be accompanied by subsequent leaching losses of potassium, magnesium and calcium. Yield responses to potassium are also likely, up to about 400 kg K_2O/ha/y. Negative potassium effects on magnesium and calcium availability may become a problem. Yield responses to P or Mg are rare in unshaded coffee in PNG. The recycling of waste products, particularly the coffee pulp, can reduce the need for fertiliser N applications by about 15%. Prunings contain significant quantities of nutrients and should therefore be fully recycled if possible.

REFERENCES

BLAKEMORE, L.C., SEARLE, P.L. and **DALY, B.K.** (1981) Methods for chemical analysis of soils. *N.Z. Soil Bureau Sc. Report 10A.* DSIR, Lower Hutt, New Zealand.

BYRNE, P.N. (1984). *Crop Research Report for the Period July 1969 to December 1982.* World Bank PNG Agricultural Support Services Project, Department of Primary Industry, Port Moresby.

CARNE, R.S. and **CHARLES, A.E.** (1966). Agronomic research on arabica coffee in Papua and New Guinea - Progress Report. *The Papua and New Guinea Agricultural Journal* 18(2): 47-61.

DASF. (1965 a). *Annual Report 1961-63.* Department of Agriculture, Stock and Fisheries, Port Moresby, Papua New Guinea.

DASF. (1965 b). *Annual Report 1963-64.* Department of Agriculture, Stock and Fisheries, Port Moresby, Papua New Guinea.

DASF. (1966). *Annual Report 1964-65.* Department of Agriculture, Stock and Fisheries, Port Moresby, Papua New Guinea

DASF. (1968). *Annual Report 1965-66.* Department of Agriculture, Stock and Fisheries, Port Moresby, Papua New Guinea.

DASF. (1972). *Annual Report 1967-69.* Department of Agriculture, Stock and Fisheries, Port Moresby, Papua New Guinea.

HARDING, P.E. (1984). *A preliminary report on the Arabica coffee soils of Papua New Guinea.* Coffee Research Report No.1. PNG Coffee Research Institute, Aiyura.

HARDING, P.E. (1985 a). The main coffee producing areas of PNG. *PNG Coffee* 4: 19-23.

HARDING, P.E. (1985 b). *A preliminary report on the Robusta coffee soils of Papua New Guinea.* Coffee Research Report No.2. PNG Coffee Research Institute, Aiyura.

HARDING, P.E. (1986). *How to collect soil and leaf samples in Papua New Guinea, and how to interpret the analytical results.* Technical Advisory Circular No.2. PNG Coffee Research Institute, Aiyura.

HARDING, P.E. (1988). The phosphorus requirements and management of coffee. *PNG Coffee* 7(2): 143-157.

HARDING, P.E. (1991 a). *Foliar nutrient level studies in smallholder coffee gardens in the Kainantu area of Papua New Guinea.* Coffee Research Report No.6. PNG Coffee Research Institute, Aiyura.

HARDING, P.E. (1991 b). *Foliar nutrient level studies in fertilised coffee in Eastern Highlands and Western Highlands Provinces of Papua New Guinea.* Coffee Research Report No.7. PNG Coffee Research Institute, Aiyura.

HARDING, P.E. (1992 a). *Investigations into the nutritional requirements of unshaded plantation coffee in Papua New Guinea: Block E7 factorial fertiliser trial, Aiyura HAES, Eastern Highlands Province, 1986/87 - 1990/91.* Coffee Research Report No.8. PNG Coffee Research Institute, Aiyura.

HARDING, P.E. (1992 b). *Nine years of coffee soil and plant nutrition research in Papua New Guinea: A review.* Coffee Industry Corporation Ltd-Coffee Research Institute, Aiyura.

HARDING, P.E. (1993 a). Seasonal fluctuations in leaf nutrient contents of fertilised and unfertilised arabica coffee in Papua New Guinea. *15th International Scientific Colloquium on Coffee*: 799-802. ASIC, Paris.

HARDING, P.E. (1993 b). *Investigations into the nutritional requirements of unshaded plantation coffee in Papua New Guinea: Block 31 factorial fertiliser trial, Koban Plantation, Western Highlands Province, 1986/87 - 1990/91.* Coffee Research Report No.9, Vols 1 and 2. PNG Coffee Research Institute, Aiyura.

HARDING, P.E. (1993 c). *Investigations into the nutritional requirements of shaded plantation coffee in Papua New Guinea: Block 31 factorial fertiliser trial, Koban Plantation, Western Highlands Province, 1986/87 - 1990/91.* Coffee Research Report No.10, Vols 1 and 2. PNG Coffee Research Institute, Aiyura.

HARDING, P.E. (1994). *A comparison of the nitrogen requirements of two coffee (*Coffea arabica *L.) management systems in Papua New Guinea.* Unpublished PhD Thesis, University of Reading, UK.

HART, G. (1969). A nutritional survey of *Coffea arabica* plantations in New Guinea. *Research Bulletin* 5: 41-76. Department of Agriculture, Stock and Fisheries, Port Moresby.

HART, G. and **SOUTHERN, P.J.** (1969). Diagnostic methods for assessing the nutritional status of New Guinea coffee. *Research Bulletin* 5: 1-12. Department of Agriculture, Stock and Fisheries, Port Moresby.

HOMBUNAKA, P.H. (1997). *Soil and Plant Nutrition Department Progress Report, April 1997 to October 1997.* Presented to Coffee Research Advisory Committee, 29 October 1997. CIC Ltd, Kainantu, Papua New Guinea.

HOMBUNAKA, P.H. and **HARDING, P.E.** (1994). The effects of timing of fertiliser applications on coffee (*Coffea arabica* L.) yields in the highlands of Papua New Guinea. *Volume 5 b: 468-469, Proceedings of the 15th International Soils Congress*, Mexico.

LINDSAY, W.L. and **NORVELL, W.A.** (1978). Development of DTPA soil test for zinc, iron, manganese and copper. *Soil Sci Soc Am J* 42: 421-428.

LING, A.H., HARDING, P.E. and **RANGANATHAM, V.** (1990). The phosphorus requirements and management of tea, coffee and cacao. In *Phosphorus requirements for sustainable agriculture in Asia and Oceania*: 383-398. IRRI, Philippines.

PARFITT, R.L. (1976). Shifting cultivation - how it affects the soil environment. *Harvest* 3: 63-66.

ROBINSON, J.B.D. (1983). *Research Service, Advisory Service, and Research Staff Training Proposals for Industry-funded Coffee Development in Papua New Guinea.* Consultant's Report to PNG Coffee Industry Board, Goroka.

SOUTHERN, P.J. (1966). Coffee nutrition - Part 1. The determination of nutritional status and fertiliser requirements of arabica coffee in New Guinea. *Papua and New Guinea Agricultural Journal* 18(2): 62-68.

SOUTHERN, P.J. (1969). The effects of fertilizer on the chemical composition of Coffea arabica leaves in New Guinea. *Research Bulletin* 5, 13-39. Department of Primary Industry, Port Moresby.

THIAGALINGAM, K. and **FAHMY, F.N.** (1981). Role of *Casuarina* under shifting cultivation. In *Nitrogen Cycling in South-East Asian Wet Monsoon Ecosystems* (eds. R.Wetselaar, J.R.Simpson and T.Rosswall): 154-156. Australian Academy of Science, Canberra.

WILLSON, K.C. (1985). Mineral nutrition and fertiliser needs. In: *Coffee - Botany, Biochemistry and Production of Beans and Beverage* (Eds. M.N.Clifford and K.C.Willson): 135-156. Croom Helm, London.

WOLF, J., DE WIT, C.T. and **VAN KEULEN, H.** (1989). Modeling long-term crop response to fertilizer and soil nitrogen. I. Model description and application. *Plant and Soil* 120: 11-22.

CHANGES IN SOIL PROPERTIES AT RAMU SUGAR PLANTATION 1979 - 1996

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ABSTRACT

This paper presents an overview of changes in soil chemical and physical properties that have resulted from continuous sugar cane cultivation at Ramu Sugar plantation since 1979. The majority of the soils at the plantation have developed in alluvial deposits and classify as Fluvisols and Vertisols. Between 1979 and 1996, the soil pH at Ramu Sugar plantation had decreased from about 6.5 to 5.8 and this was accompanied by a decrease in CEC and exchangeable cations. Organic C levels had declined from about 56 g kg^{-1} in 1979 to 32 g kg^{-1} in 1996. The interrow of the sugar cane was compacted and had significantly higher bulk densities and a very slow water intake. Semi-quantitative nutrient budgets showed a shortfall in N, P and K, and levels of these nutrients in the sugar cane leaves had significantly decreased between the mid 1980s and 1990s. Yields at the plantation are largely determined by the insect pests, diseases and weeds. It is concluded that significant soil changes occurred at Ramu Sugar plantation and despite the fact that most soil chemical properties are still favourable for sugar cane cultivation, a change in soil management is required.

Keywords: *soil fertitility decline, soil compaction, soil acidification, soil management.*

INTRODUCTION

Plans for establishing a sugar cane plantation in Papua New Guinea date back to the 1930s when the 'The Singara Sugar Estates Ltd' proposed to establish a plantation near Buna in the Northern Province (Van der Veer 1937). The plantation was never established and in the decades that followed various reports suggested that commercial sugar cane production was technically feasible (e.g. Krishnamurthi 1976). It was emphasized that it would be a great risk because Papua New Guinea is the centre of origin of sugar cane and has therefore a broad range of pests and diseases (Szent-Ivany and Ardley 1962; Li 1985). When by the mid 1970s the demand for sugar increased and world market prices fluctuated strongly, the government decided to establish a national sugar industry. The decision was part of Papua New Guinea Eight Aims that included a more self-reliant economy and the ability to meet the needs of its people through local production. Initial investigations were carried out in the Markham valley for identifying a suitable site, which could produce about 30,000 to 40,000 t sugar annually. Several potential sites were identified but the Gusap-Dumpu area on the north bank of the Ramu river was favoured because it did not need irrigation or flood-protection works and land preparation costs were lower (Chartres 1981). In 1979, a detailed soil survey was undertaken and about 7,000 ha of suitable or moderately suitable land in the Gusap-Dumpu area was identified (Booker Agriculture International 1979). The first sugar cane was planted in 1979 and the plantation was named Ramu Sugar Ltd. The area under cane grew rapidly from 1,592 ha in 1981 to 5,011 ha in 1983 (Eastwood 1990).

There are few plantation crops in the tropics that put such heavy demand on soil resources as sugar cane. Most commercial sugar cane is grown intensively on a large scale and many of the husbandry practices are similar to intensive agricultural systems in temperate regions. Heavy machinery is used for land preparation, planting, spraying and harvesting. Biocides are widely used to control pests

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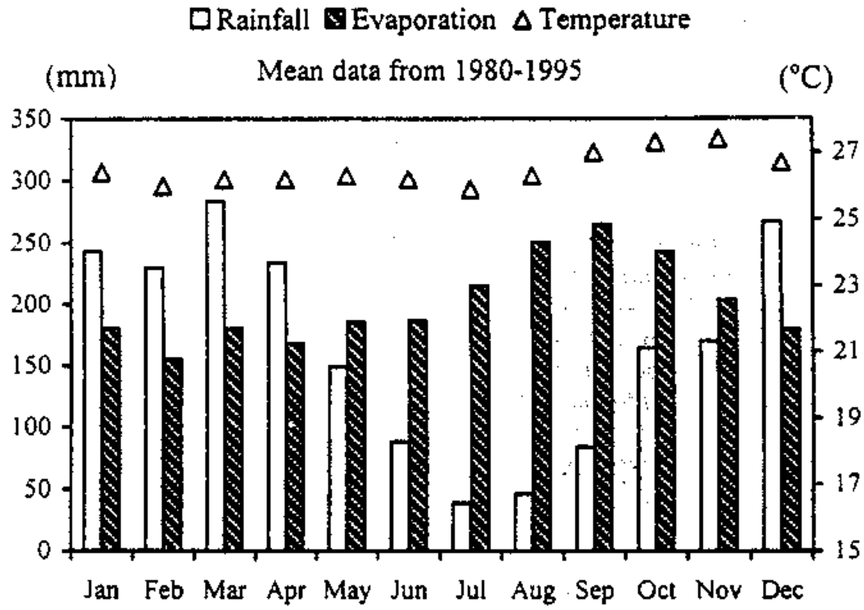
Figure 1. **Mean monthly rainfall, evaporation and temperature at Ramu Sugar Ltd.**



and diseases, herbicides to control weeds, and inorganic fertilizer applications to sustain yields. Sugar cane also makes heavy demands on soil nutrient reserves as large amounts of nutrients are removed with the harvest. Unless replaced either naturally through weathering and bio-geocycling, or artificially through inorganic fertilizers or with for example filter press cake, the soil nutrient pools will decline. In summary, commercial sugarcane cultivation is likely to affect soil conditions.

At Ramu Sugar Ltd, relatively little is known on changes in soil properties resulting from continuous sugar cane cultivation. In 1996 and 1997, we therefore collected all available soil analytical data at the plantation and compared these to changes in leaf nutrient concentration. In order to explain some of the observed trends, semi-quantitative nutrient balances were developed and these were compared to long-term trends in leaf nutrient concentration. This paper summarizes the major research findings including a description of the environmental conditions at Ramu Sugar Ltd.

THE ENVIRONMENT

Ramu Sugar Ltd (6°S, 146°E) is located in the Madang Province. Prior to the planting of sugar cane in 1979, the site was under natural grassland with some forest and swamp vegetation in poorly drained and low-lying areas. The grassland was dominated by *Imperata cylindrica* (kunai) which was found on the deeper and fine textured soils (Booker Agriculture International 1979). Its dominance was probably due to the annual burning as Imperata regenerates rapidly compared with other species (Henty and Pritchard 1988). On shallower and stony soils *Themeda australis* (kangaroo grass) dominated the natural vegetation whereas *Saccharum spontaneum* and *Ophiuros* sp. in the wetter sites along streams and rivers (Chartres 1981).

Climate

The plantation is in an area which is directly affected by the passage of the Inter-Tropical Convergence Zone which occurs twice yearly (Chartres 1981). Consequently, there is a seasonal rainfall pattern (uni-modal) with a dry season from May to November and a rainy season from December to April. The average rainfall at the plantation is 1998 mm y^{-1} but between 1980 and 1995 annual rainfall has varied from 1531 to 2560 mm. June to September are the driest months with an average of less than 90 mm per month (Figure 1). March is the wettest month with an average rainfall of 284 mm. Evaporation (Class A open pan) is about 2281 mm y^{-1} and exceeds rainfall from May to November. Mean annual temperatures are 26.7°C with only minor fluctuations through the year. The climate classifies as Am (Köppen) i.e. a tropical rainy climate with a short dry season.

There is very little relation between total annual rainfall and sugar cane yields. An index often used in the evaluation of water and sugar cane is the production of sugar per mm of rain (Fauconnier 1993). These values were calculated from the yield and climatic data. It was found that in the past fifteen years between 21.2 and 40.9 mm of rain was required to produce 1 t cane ha^{-1} which is equivalent to 2 to 4.2 kg sugar ha^{-1} per mm of rain.

Land management under sugar cane

The first three ha of sugar cane were planted in 1979 but the total area under sugar cane grew rapidly from 1592 ha in 1981, to 5011 ha in 1983 and to 6030 ha in 1995. The plantation was established for rainfed sugar cane production. Feasibility studies for irrigation have been conducted in the past but it was soon realised that other constraints were more important. About 1,800 ha of sugar cane are planted mechanically each year. Up to 1994, planting took place at the beginning of the wet season (September to November) but currently most of the cane is planted from late February to May as it was found to reduce the risk of certain insects pests. The harvesting season lasts from May to October and cutter-chopper-loader harvesters are used with 20 tonnes tractors and trailers transporting the cane to the factory. Most of this equipment has conventional tyres. About half of the sugar cane is trash-harvested (no pre-harvesting burning). Up to five crops (i.e. plant cane + four ratoons) are sometimes obtained after which the land is replanted or sometimes cowpea (*Vigna unguiculata*) is sown which is ploughed under after one year. Prior to 1989, nitrogen fertilizer was applied as urea (46% N) but when trash-harvesting replaced pre-harvesting burning, it was suggested that considerable amounts of urea-N would be lost through volatilization. Therefore nitrogen fertilizer supplied after 1989 was in the form of sulphate of ammonia (21%N) and on average 90 kg N $ha^{-1} y^{-1}$ as applied during the period 1991 to 1995. Nitrogen applications are mostly broadcasted between August and November. Phosphorus and potassium fertilizers are not applied.

Geomorphology

The Ramu valley is drained by the perennial Ramu river and several tributaries with erratic flow characteristics. The valley covers an area of about 7500 km^2 (Bain and Mackenzie 1975) and forms together with the Markham valley a large *graben* which has been a zone of subsidence since the Late Tertiary period (Löffler 1977). At the site of the plantation, the valley is about 10 km wide. The Ramu valley contains about 2000 m of unconsolidated and poorly consolidated Quaternary marine and terrestrial clastic sediments overlying Tertiary sedimentary rocks (Bain and Mackenzie 1975). The valley comprises a series of alluvial fans and some of these fans are incised by their streams forming deep gullies (> 20 m). Slopes are up to 5% on the higher parts of the fans but decrease downslope to less than 0.5%. Altitude at the site of the plantation is about 400 m a.s.l. Since the plantation is situated in a tectonically active area, geomorphologic processes are currently visible. In November 1993, a landslide dammed an important drainage way in the lower part of a catchment area of the Finisterre Mountains. A lake formed behind the dam that collapsed after several days of heavy rain. The massive mudflow that followed filled the deeply incised Gusap and Bora streams and washed out the Lae-Madang road and several hectares of sugar cane. Drainage of soils adjacent to the Gusap stream was then retarded and some sugar cane land had to be abandoned because of poor workability. Although such mudflows quite catastrophically affect the sustainability of sugar cane growing they do not affect large areas and are not further considered in this study.

Soils

The parent material of the soils at the plantation is alluvium. The soils have been developed in clayey, silty and sandy sediments and from the weathering products of the water-worn stones and boulders of varying lithology. The stones and boulders originate from sandstone, siltstone and limestone, but also from basalt and igneous rocks with coarser textures. The coarse material is generally poorly sorted and there is a gradual decrease in grain size from the Finisterre Mountains towards the Ramu River. Although deep and nearly gravel free soils

Table 1. **Soil chemical and physical properties of a Fluvisol and Vertisol at Ramu Sugar plantation.**

Soil type	Sampling depth (m)	pH H_2O 1:2.5	pH KCl 1:2 5	Organic C (g kg^{-1})	Total N (g kg^{-1})	P-Olsen (mg kg^{-1})	CEC pH7 (mmol$_c$ kg^{-1})	Exchangeable cations (mmol$_c$kg^{-1})			Base saturation (%)	Particle size fractions (g kg^{-1})		
								Ca	Mg	K		clay	silt	sand
Fluvisol	0-0.15	6.2	5.0	16.5	1.4	35	311	185	95	7.6	93	300	300	400
	0 15-0.30	6.1	4.9	14.0	1.2	21	302	208	103	4.7	100	280	360	360
	0 30-0.45	6.2	5.1	14.3	1.2	14	435	332	148	3.0	100	480	390	130
	0 45-0.60	6.1	5.0	18.1	1.4	11	530	430	169	2.4	100	750	230	20
Vertisol	0-0.15	5.9	4.7	29.8	1.8	32	540	272	115	9.4	74	550	160	290
	0.15-0.30	6.1	4.6	31.3	1.8	33	517	274	118	12.4	78	530	90	380
	0.30-0.45	6.3	4.8	19.8	1.2	15	546	287	123	3.3	76	590	180	230
	0.45-0.60	6.2	4.8	12.5	1.0	9	531	236	99	2.2	64	530	200	270

Table 2. **Topsoil (0-0.15 m) chemical properties between 1979 and 1996 at Ramu sugar plantation (arithmetic mean ±1 SD).**

Year	Number of Samples[a]	pH H_2O 1:2.5	Organic C (g kg^{-1})	Total N (g kg^{-1})	Available P (mg kg^{-1})	CEC pH 7 (mmol$_c$ kg^{-1})	Echangeable cations (mmol$_c$kg^{-1})			Base saturation (%)
							Ca	Mg	K	
1979[b]	21	6.5 ± 0.3	56.5 ± 13.8	2.8 ± 0.5	n.a.	398 ± 41	246 ± 80	101 ± 42	13.5 ± 4.4	83 ± 18
1982	78	6.2 ± 0 1	n.a.	n.a.	38 ± 5	456 ± 46	268 ± 31	116 ± 19	13.9 ± 2.5	87 ± 2
1983	226	6 3 ± 0.2	n.a.	2.2 ± 0.3	37 ± 11	448 ± 77	267 ± 61	105 ± 23	12.3 ± 2.8	86 ± 6
1984	50	6.2 ± 0.2	n.a.	n.a.	36 ± 14	427 ± 65	260 ± 52	100 ± 23	11.1 ± 3.1	87 ± 3
1985	19	6.1 ± 0.2	n.a.	n.a.	37 ± 15	482 ± 48	293 ± 67	113 ± 31	11.1 ± 3.7	87 ± 3
1986	29	6.1 ± 0.2	n.a.	n.a.	35 ± 19	435 ± 93	262 ± 67	103 ± 32	11.7 ± 7.3	86 ± 4
1991	25	6.2 ± 0.2	n.a.	n.a.	24 ± 14	386 ± 95	326 ± 47	99 ± 52	10.5 ± 3.2	88 ± 10
1994	60	5.9 ± 0.1	33.4 ± 5.2	1.9 ± 0.3	28 ± 10	403 ± 76	248 ± 50	109 ± 28	11.7 ± 3.1	92 ± 11
1996	30	5.8 ± 0.3	32.1 ± 5.5	1.9 ± 0.4	26 ± 11	411 ± 78	263 ± 62	106 ± 27	9.3 ± 3.5	91 ± 7

n.a. not available.

[a] Composite topsoil samples of continuouly cultivated fields, except for 1979.

[b] Soil samples taken prior to the establishment of the plantation.

(>1.2 m depth) occur, extensive areas have gravelly (5 to 15%) topsoils and very gravelly (15 to 40%) or stony subsoils. The pH H_2O values of the soils are around 6.0 indicating no apparent danger from exchangeable aluminium or excess $CaCO_3$ Soil salinity is not a problem in the topsoils but the deeper subsoils are slightly alkaline. Sheet and gully erosion is a threat in some areas but terraces have been dug across the contour to control surface water.

Fluvisols are the dominant Major Soil Grouping at the plantation. At the soil unit level in FAO-Unesco, the Fluvisols are Eutric or Mollic, equivalent to the great group of Tropofluvents (Entisols) in USDA Soil Taxonomy. Some Entisols classify as Tropopsamments (Bleeker 1983). The soil temperature regime is isohyperthermic and the soil moisture regime udic indicating that in most years the soils are dry for less than 90 cumulative days per year. Shrinking and swelling dark clay soils (Vertisols) cover about one quarter of the sugar cane plantation. These soils are dominated by montmorillonite or some other smectite mineral. During the fieldwork (January, August and October 1996, April 1997) cracks were observed in these soils but not to 0.5 m depth as is required for the soils to be classified as Vertisols (FAO-Unesco 1988). The absence of deep cracks may have been caused by frequent tillage and high contents of stable aggregates which commonly occur in Vertisols when the organic matter content is 30 g kg^{-1} or more (Ahmad 1984). The soils are, however, likely to be Vertisols because of the presence of wedge-shaped structural elements, slickensides in the subsoil, the fine texture (> 500 g clay kg^{-1} soil), and the hard consistency and cracks when dry. The soils contain no calcareous concretions which are commonly absent in Vertisols under high rainfall (Blokhuis 1980). At the soil unit level in FAO-Unesco, these soils are Eutric Vertisols, equivalent to the great group of Hapluderts in USDA Soil Taxonomy (Soil Survey Staff 1994). Soil chemical and physical data of a representative Eutric Fluvisol and Eutric Vertisol are given in Table 1.

In some low-lying areas, soils with poor internal drainage occur and these are classified as Gleysols in FAO-Unesco (1988). According to Booker Agriculture International (1987) they cover only a small area of the plantation (ca. 3% or 180 ha) and data from these soils were not included in this study.

Some sugar cane is planted at the footslopes of the Finisterre Mountains in soils derived from a mixture of alluvial and colluvial deposits. Very locally, these soils have been enriched with tephra probably originating from Long Island in the Bismarck Sea (Parfitt and Thomas 1975). Such soils may contain up to 10% allophane and have high phosphorus retention capacities (Loveland 1991). Since these soils are confined to a small area and have not received much research attention, they were excluded from this study.

MATERIALS AND METHODS

To investigate changes in soil chemical properties and leaf nutrient concentrations, we collected all available analytical data from 1978 to 1995. In addition we collected sugar cane production data from the whole plantation and divided this by the area under cane to obtain yield figures. Also the total annual fertilizer consumption of Ramu Sugar Ltd was divided by the area under cane to obtain fertilizer applications per hectare. For the changes in soil physical properties, no historical data could be used and we made bulk density and water intake measurements under sugarcane and adjoining grasslands.

Soil chemical data

With the establishment of the plantation in 1979, the area was divided into blocks of 10 to 20 ha. Between 1982 and 1994 soil samples were taken in most sugar cane blocks for routine analysis and the analytical data of 487 topsoil (0-0.15 m) and some 50 subsoil samples was available. Also the chemical data of 21 soil profiles (15 Fluvisols, 6 Vertisols) from the initial soil survey report was available (Booker Agriculture International 1979). The topsoil samples between 1982 to 1994 were commonly taken after the last ratoon when the sugar cane was ploughed-out. Samples were bulked from 20 to 50 locations in a sugar cane block using an Edelman auger. The samples taken in 1996 were composites from 10 to 15 locations in a sugar cane block and mini-pits were used for the 0-0.15 soil horizons. All soil samples of 1996 were taken in the interrow of the sugar cane.

Airdried, ground and sieved samples (2 mm) were analyzed at the Cambridge Laboratory in Cambridge (New Zealand) or at the National Analytical Chemistry Laboratory in Port Moresby (Papua New Guinea). The procedures for soil analysis were identical at both laboratories, and as follows: pH H_2O in 1:2.5 or 1:5 suspension of soil and water; pH KCl in a 1:2.5 soil and 1*M* KCl solution; organic carbon by $K_2Cr_2O_7$ and H_2SO_4 oxidation (Walkley & Black); total N by Kjeldahl; available P by $NaHCO_3$ extraction (Olsen); exchangeable cations Ca, Mg, K, Na and CEC percolation by 1*M* NH_4OAc followed by spectrophotometry (K, Na), AAS (Ca, Mg) and titration (CEC); particle size analysis by hydrometer. The soil samples of the initial soil survey (Booker Agriculture International 1979) were analyzed at the laboratories of Hunting Technical Services Ltd in England. Except for available P, all other methods were identical to the ones described above.

Soil physical data

Infiltration measurements were made using the double ring (cylinder) method with measurements confined to the inner-ring. Four sugar cane blocks (2 Eutric Fluvisols, 2 Eutric Vertisols) were selected bordering a natural grassland area with the same soil profile as under sugar. The sugar cane at the infiltration sites was in the second or third ratoon. In each sugar cane block, infiltration measurements were made in triplicate at about 10 m from each other. Measurements were made between the sugar cane rows (interrow), and within the rows (between two stools). At about 75 m from the sugar cane block, infiltration measurements were made in natural grassland and also these measurements were triplicated. Although the infiltration measurements were made in periods with ample rain, particularly during the night (November 1996 and April 1997), most infiltration sites were prewetted 24h prior to the measurements using borehole water. Infiltration readings were made every min for the first 10 min, every 2 min between 10 and 20 min, and every 15 min between 20 and 320 min. Mean infiltration rates (mm h^{-1}) were calculated for the first 10 min (10 readings) and between 20-80 min (5 readings), 140-200 min (5 readings) and 245-305 min (5 readings) after the rings were filled with water. In total 36 infiltration measurements were made of at least 5h each but in most measurements the steady state was reached within 4h.

At the same sites where the infiltration measurements were made, soil pits were dug (± 1 m depth) for bulk density measurements. At each site, one soil pit was dug in the sugar cane block and one in the adjoining natural grassland area. In total 8 soil pits were sampled using cores (100 mL) which were gently pushed into the soil at four depths: 0-0.15, 0.15-0.30, 0.30-0.50, 0.50-0.70 m. Because of abundant gravel in the 0.50-0.70 soil horizon of the Fluvisols, the bulk density could not be accurately determined with 100 mL cores as their volume is much too small. In the soil pits under sugar cane, both the interrow and the soil horizons between the rows were sampled. Three cores were used for each depth and they were ovendried at 105°C for 72h. In total 126 core samples were taken at the infiltration sites and an additional 18 cores were taken in 2 other soil pits at the plantation.

Leaf nutrient data

About 600 foliar samples for the analysis of macronutrients (N, P, K, Ca, Mg, S) were taken between 1982 to 1996. Leaf samples at Ramu Sugar Ltd were commonly taken after the onset of the rainy season (December-February) when growth rates are high. For the leaf sampling, 21 rows were selected randomly within a block. At 30 to 40 paces the fourth leaf was sampled from a nearby stool; the first leaf was the unfurl leaf. About 400 to 600 leaves of which the midrib was removed, were composited of which a subsample was taken. Leaf samples were dried at 80°C for 48 hours. All leaf samples were analyzed at the Cambridge laboratory in New Zealand following standard analytical procedures.

RESULTS

Soil chemical properties

Between 1979 and 1996, the topsoil pH_w (pH H_2O) decreased from about 6.5 to 5.8 (Table 2). The initial decrease in pH_w from grassland (1979) to sugar cane (1982) may have been caused by the increased mineralisation of organic matter which is a common cause for soil acidification (Rowell and Wild 1985). The rapid pH_w decline observed in the 1990s coincides with the change in fertilizer policy from urea to sulphate of ammonia which has twice the potential acidity. It may also be due to the large addition of organic matter with the trash-harvesting as in some studies such additions were found to decrease the soil pH (Pocknee and Sumner 1997). The soil acidification was accompanied by a change in the levels of exchangeable bases. Particularly

Table 3. **Changes in soil chemical properties (0-0.15 m) of Fluvisols and Vertisols under sugarcane between the 1980s 1990s.**

	Fluvisols (n=7 pairs)			Vertisols (n=5 pairs)		
	1982 -1983	1991 -1994	difference	1982 -1983	1991 -1994	difference
pH H_2O (1:2.5 w/v)	6.3	5.9	P<0.001	6.4	6.0	P<0.001
available P (mg kg^{-1})	37.2	29.0	P=0.04	35.4	24.6	n.s.
CEC ($mmol_c$ kg^{-1})	412	354	P<0.001	450	403	n.s.
exchangeable Ca ($mmol_c$ kg^{-1})	229	213	n.s.	269	250	n.s.
exchangeable Mg ($mmol_c$ kg^{-1})	100	94	n.s.	109	95	n.s.
exchangeable K ($mmol_c$ kg^{-1})	11.0	9.5	n.s.	13.0	10.1	n.s.
base saturation (%)	83	88	P=0.02	87	88	n.s.

n.s. not significant

Table 4. **Bulk density[a] (kg dm^{-3}) of Fluvisols and Vertisols under sugar cane and natural grassland.**

		Land-use			
Major soil Groupings	Sampling depth (m)	Sugar cane within the rows	Sugar cane interrows	Natural grassland	SED[c]
Fluvisols[b]	0-0.15	1.10	1.29	1.07	0.04
	0.15-0.30	1.18	1.34	1.17	0.06
	0.30-0.50	1.35	1.39	1.26	0.05
Vertisols	0-0.15	0.98	1.18	1.00	0.03
	0.15-0.30	1.08	1.19	1.02	0.05
	0.30-0.50	1.14	1.21	1.12	0.06
	0.50-0.70	1.13	1.22	1.17	0.06

[a] values reported are the arithmetic mean of 6 core samples of 100 mL taken in 2 soil pits.
[b] the 0.50-0.70 m soil horizons could not be sample accurately with 100 mL cores because of abundant gravel.
[c] standard error of the difference in means (10 *df*).

the levels of exchangeable K declined possibly due to a combination of the large K removal by the sugar cane (Yates 1978) and leaching losses. Organic C levels declined by about 40% between 1979 and 1996. For high yielding sugar cane, however, maintenance of favourable organic matter levels is important (Yadav and Prasad 1992). Levels of available P declined but variation was large. Topsoil data of the same sugar cane block but from different times revealed a significant decline in pH_w, available P, CEC and base saturation in Fluvisols (Table 3). In the Vertisols, a highly significant decline of 0.4 pH_w units was found whereas changes in other soil chemical properties were not significant.

Soil physical properties

Bulk densities under natural grassland and within the sugar cane rows were similar for all depths of both Fluvisols and Vertisols (Table 4). The bulk densities in the interrow were, however, significantly higher in the two Major Soil Groupings and in all soil pits it was observed that roots were absent in the interrow which commonly is found in compacted soils under sugar cane (Trouse and Humbert 1961). The compaction in the interrow of the sugar cane was caused by wheel traffic during harvesting and other field operations. In the Vertisols, there was no difference below 0.3 m depth whereas in the

Fluvisols the bulk density of the interrow was also higher in the 0.30-0.50 m soil horizon. The absolute increase in the topsoil bulk density of the interrow as compared to natural grassland was 0.22 kg dm^{-3} (+21%) in the Fluvisols and 0.18 kg dm^{-3} (+18%) in the Vertisols. Overall, Fluvisols had significantly higher bulk densities than the finer textured Vertisols.

Cumulative water intake of natural grassland and within the sugar cane rows was very high in both Major Soil Groupings (Figure 2). The high water intake of the Vertisols is puzzling as it is commonly found that such soils have a low water intake when wet (Ahmad 1983). There may have been some lateral flow which is common in double-ring infiltrometers (Lal 1979) and this may be enhanced in crops grown on ridges like sugar cane. Variation in cumulative water intake was larger in the Fluvisols than in Vertisols possibly due to the non-uniformity of the Fluvisol profile with layers having different hydraulic conductivities (Bouwer 1986). Within the sugar cane rows, cumulative infiltration rates after 5h were 1322 mm in the Fluvisols compared to 1200 mm in the Vertisols. Water intake in the interrow was very low and had not exceeded 105 mm in Fluvisols and 59 mm in Vertisols after 5h. Amongst others, the slow water intake in the interrows may result in soil erosion which can be particularly high on Vertisols (Unger and Stewart 1988) and under sugar cane (Prove *et al.* 1995) but there were no data available to verify this.

Table 4 and Figure 2 provide evidence for significantly higher bulk densities and lower infiltration rates in the interrow of sugar cane. To investigate the relation between the two, mean infiltration rates were plotted against topsoil bulk densities for Fluvisols and Vertisols (Figure not shown). A negative exponential relation was observed i.e. a rapid decrease in water intake with increasing bulk densities. For both Fluvisols and Vertisols, a high correlation (r^2>0.8) was found between bulk density and mean infiltration rates. Bulk densities at which mean infiltration was above 100 mm h^{-1} after 4h, were 1.15 kg dm^{-3} for Fluvisols and 1.04 kg dm^{-3} for Vertisols. Bulk densities at which infiltration rates were 50 mm h^{-1} during the first 10 min, were 1.20 kg dm^{-3} for Fluvisols and 1.16 kg dm^{-3} for the Vertisols.

***Figure** 2.* **Cumulative infiltration of Fluvisols and Vertisols at Ramu sugar Ltd. Vertical bars represent the largest standard deviation for measurements at an infiltration interval.**

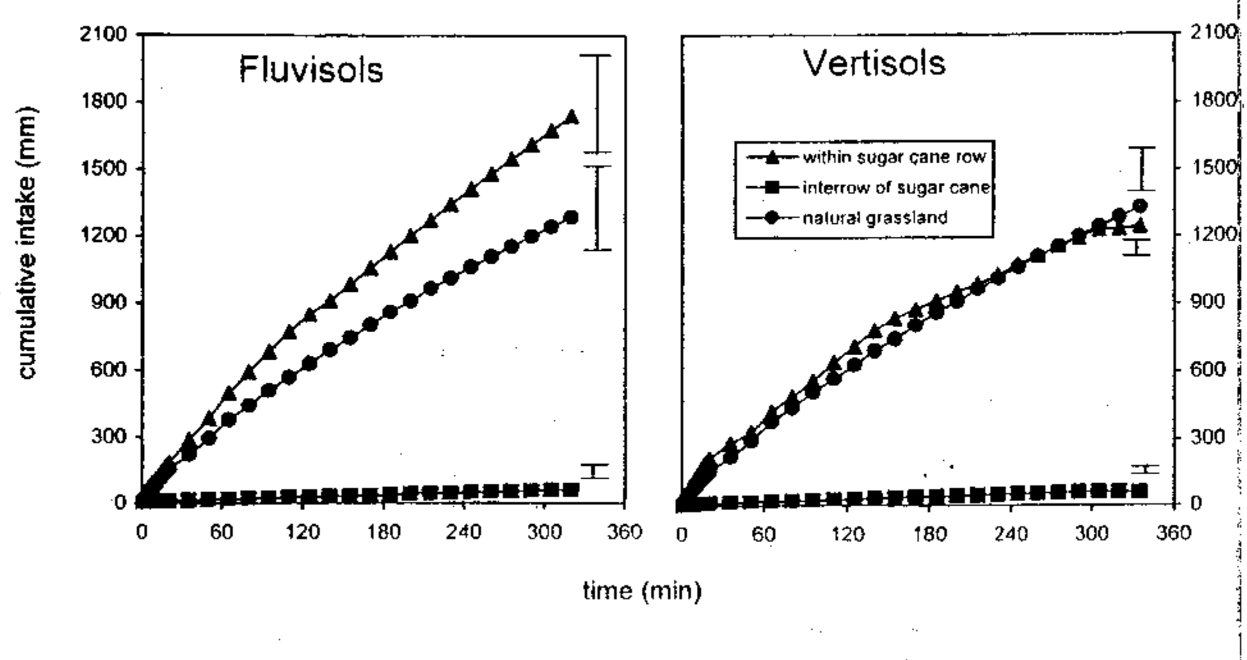


***Table 5.* Nutrient removal (range) and nutrient input with fertilizers between 1991 and 1995.**

	Nutrient removal (kg ha^{-1})						Fertilizer applications (kg ha^{-1})			Difference (kg ha^{-1})					
	N		P		K		N	P	K	N		P		K	
	low	high	low	high	low	high				low	high	low	high	low	high
1991	27	57	8	17	48	119	34	12	0	7	-23	4	-5	-48	-119
1992	33	71	9	21	59	148	115	4	0	82	44	-6	-17	-59	-148
1993	28	60	8	17	50	124	105	1	0	77	46	-7	-16	-50	-124
1994	35	75	10	22	62	156	81	0	0	47	7	-10	-22	-62	-156
1995	35	75	10	22	63	156	83	3	0	48	8	-7	-19	63	-156

[a] highest and lowest removal values as given by Hunsigi (1993) multiplied by the sugarcane yield from the plantation

***Table 6.* Mean difference (kg ha^{-1}) between nutrient removal and nutrient input.**

	N	P	K
1991	-8	-1	-84
1992	+63	-12	-104
1993	+62	-12	-87
1994	+27	-16	-109
1995	+28	-13	-110

Nutrient budgets

Changes in soil chemical properties indicated a decline in plant nutrient availability. In this section, we shall look at a possible explanation based on a comparison between nutrient inputs and nutrient outputs. Yield data (t ha^{-1}) from 1991 to 1995 were multiplied with a range of nutrient removal data (kg nutrient per t ha^{-1}). These were compared with the nutrients applied in the fertilizers and the difference was calculated for the low and high range (Table 5). It appeared that the difference between N removal and N applied was positive whereas for P and K a negative difference between removal and fertilizer application was found. Table 6 presents the mean differences for the three major nutrients. However, this assumes a 100% efficiency of the fertilizers, which never occurs, and in reality, the balance is therefore much more negative.

Leaf nutrients

Median nitrogen contents in the cane leaves at Ramu Sugar Ltd varied from 19.3 to 22.0 g kg^{-1} between 1983 to 1994 (Table 7). The lowest figure was the median of the 27 leaf samples taken in 1994. There appears to be a declining trend in the phosphorus contents of cane leaves but the median value of 2.4 g kg^{-1} in 1994 is still above the optimum concentration of 1.8 g kg^{-1} as given by Anderson and Bowen (1990) and 2.1 g kg^{-1} as given by De Geus (1973). The apparent trend in leaf phosphorus decline coincides with the decrease observed in the levels of available P in the topsoils (Table 3). Leaf potassium contents were favourable from 1983 to 1989 but the median value in 1994 is at the lower border of the optimum range of 12.5 g kg^{-1} (Anderson and Bowen 1990; De Geus 1973). Levels of sulphur, calcium and magnesium show no apparent trend and all medians values are in the optimum range.

***Table 7.* Macronutrient concentrations (g kg^{-1}) of sugar cane leaves at Ramu Sugar plantation (mediam values with CV %).**

Year	no. of samples	N	P	K	S	Ca	Mg
1983	481[a]	22.0 (11%)	3.5 (16%)	15.0 (14%)	1.3 (12%)	2.9 (16%)	1.8 (12%)
1987	69	20.0 (13%)	2.7 (9%)	16.0 (15%)	1.8 (14%)	4.4 (16%)	2.5 (14%)
1989	24	21.0 (12%)	2.9 (17%)	16.1 (15%)	1.8 (30%)	3.5 (21%)	1.7 (17%)
1994	27	19.3 (10%)	2.4 (7%)	12.5 (11%)	n.a.	3.1 (20%)	1.3 (17%)

[a] there were only 11 samples of sulphur, calcium and magnesium in 1983.
n.a. not available

***Table 8.* Macronutrient concentrations (g kg^{-1}) of sugar cane leaves in the 1980s and 1990s.**

Period	no. of Samples	N	P	K	Ca	Mg
1985-1987	93	20.3	2.8	14.7	4.4	2.4
1994-1996	160	19.4	2.6	13.8	2.8	1.6
Difference		$p<0.001$	$p<0.01$	$p<0.001$	$p<0.001$	$p<0.001$

***Table 9.* Critical nutrient concentration (g kg^{-1}) and % samples below this level in the 1980s and 1990s.**

	N	P	K	Ca	Mg
Critical nutrient concentration[a]	19.0	2.0	13.0	1.5	1.0
% sample <critical level in mid 1980s	17	1	23	0	0
% sample <critical level in mid 1990s	40	17	47	1	3

[a] based on data for +4 leaf in: De Geus (1973), Orlando Filho (1985), Anderson and Bowen (1990), Srivastava (1992), and Malavolta (1994)

All major nutrients in the sugar cane leaves had decreased significantly between the mid 1980s and 1990s (Table 8). The largest decrease was found in the Ca and Mg concentrations, which had decreased with 36 and 33%, respectively. Small but highly significant differences were found between the P concentrations of the mid 1980s and 1990s. Several keys to the interpretation of leaf nutrients concentration for sugar cane exist, but much depends on the age of the plant at sampling, the sugar cane variety, the plant part sampled, soil conditions and fertilizer applications. The first row in Table 9 summarizes the critical nutrient concentration for the fourth leaf as compiled from several sources. The mean nutrient concentrations in both the mid 1980s and 1990s (Table 8) were exceeding the critical level. However, the percentage samples below the critical level increased dramatically between the mid 1980s and 1990s (Table 9). The increase was particularly high for N and K, and the data showed that in the mid 1990s about 40% of the samples was below the critical N concentration whereas 47% of the samples was below the critical K concentration. Although Ca and Mg

Table 10. **Estimated average yield loss (t ha^{-1} y^{-1}) by insect pests, diseases and weeds (Hartemink and Kuniata 1996).**

year	insects pests and diseases				weeds	total estimated loss	actual yield
	moth stem borer	cicadas	white grubs	Ramu stunt			
1984	-	-	7	-	-	-	65
1985	-	-	7	15	-	-	50
1986	18	-	4	27	-	-	27
1987	31	-	0	1	5	-	64
1988	12	-	0	0	1	-	86
1989	8	4	0	0	20	32	53
1990	11	22	0	0	22	55	49
1991	4	16	0	0	18	38	48
1992	3	3	0	0	24	30	59
1993	0	1	0	0	26	27	50
1994	2	0	1	0	17	20	61
1995	10	1	<1	0	5	17	62

- means unknown or not quantified

concentrations had decreased dramatically (Table 8), there were only very few values in the mid 1990s below the critical levels.

Sugar cane yields

Mean sugar cane yields at Ramu Sugar Ltd have varied in the past fifteen years from 28 to 88 t ha^{-1} y^{-1} and sugar yield varied from 2.0 to 8.2 t ha^{-1} y^{-1}. Regression analysis of cane and sugar yield showed a strong linear relationship and the sugar content of the cane is about 9% (sugar yield = 0.09 * cane yield - 0.29; r^2 =0.942). Much of the variation in sugar cane yields can be explained by pests and diseases, some of which can have a high impact on yield if poorly controlled (Table 10).

Ramu stunt was first observed in 1985 and in 1986, the disease was widespread in the sugar cane variety Ragnar that occupied most of the plantation. The rapid decrease between 1982 and 1986 can therefore be explained by the incidence of Ramu stunt disease. The disease was so severe that it could have caused the closure of the plantation (Eastwood 1990). Also the white grub was present in 1984 and 1985 but its effects were not very obvious although potential losses of up to 36 t cane ha^{-1} y^{-1} can be expected if the infestation is severe (L.S. Kuniata unpublished data). As a result of the Ramu stunt, most of the sugar cane was replanted in 1986 with the resistant variety Cadmus. However, Cadmus appeared to be very susceptible to the moth stem borer and in 1987, a severe outbreak was observed damaging up to 60% of the crop resulting in 18% reduction in sugar production (Kuniata and Sweet 1994). Average cane yields in 1988 were substantial higher because of the prolonged droughts in 1987 that significantly reduced the number of stem borers. Also larvae of the moth stem borers were controlled by applications of carbofuran insecticides in 1988. Yield dropped again sharply in 1989 due to the outbreak of cicadas, reducing yields to about 50 t cane ha^{-1}. The cicadas were controlled by ploughing-out followed by a fallow period of two to four months. This was effectively practised from 1989 onwards. Since the late 1980s yields have stabilized at around 55 to 60 t cane ha^{-1} y^{-1}. Such low yields can be explained through the planting of varieties resistant to pests and diseases, but these varieties have generally a low yield potential. Highly productive varieties were considered again in 1993 resulting in higher yields but also a higher population of moth stem borers in 1995 and 1996. Yields are also limited by the competition between sugar cane and weeds. Dominant weeds at Ramu Sugar Ltd are itchgrass (*Rottboellia* sp.) and nutgrass *Cyperus rotundus* and weed competition trials have shown that itchgrass can give yield reductions of up to 54 t cane ha^{-1} (L.S. Kuniata unpublished). In commercial fields, an average loss of 26 t cane ha^{-1} was observed in 1993 but losses were reduced to 5 t cane ha^{-1} in 1995 as a result of improved weed control measures (Table 10). It confirms the general belief that sugar cane does not tolerate competition for water and nutrients.

Table 10 shows that between 1982 and 1995 sugar cane yields were largely determined by insect pests, diseases and weeds. These factors are likely to mask the effects of the changes in soil properties on sugar cane yields.

DISCUSSION AND CONCLUSIONS

In the past 17 years significant changes in soil chemical and physical properties occurred at Ramu Sugar plantation. These changes reflect the way in which the soils were managed including continuous cultivation with acidifying N fertilizers, the absence of P and K fertilizers, and the use of heavy machinery. Soil chemical and physical properties have changed but did they reach levels that affect the sugar cane?

The pH levels in 1996 were about 5.8. Although the optimum pH for sugar cane is about 6.5 (Yates 1978), sugar cane is successfully grown on soils with pH 4 as in Guyana to soils with pH over 7 as in many parts of Barbados. It is therefore unlikely that the current pH levels affect sugar cane production. Levels of available P (Olsen) were on average over 25 mg kg^{-1} which are high levels for sugar cane (Blackburn 1984). Also the exchangeable cations remained at favourable levels for sugar cane cultivation. It suggests that the soil chemical properties had not reached threshold values for sugar cane cultivation despite their significant decline. Threshold values in bulk density were, however, reached because in all soil pits it was observed that roots were absent in the interrow. These values are about 1.3 kg dm^{-3} for the Fluvisols and 1.2 kg dm^{-3} for the Vertisols topsoils and they are only slightly higher for the subsoils. Absolutely seen, they are low (<1.4 Mg m^{-3} and most studies with sugar cane have indicated critical bulk densities up to 1.8 and 1.9 Mg m^{-3} for rooting (Blackburn 1984). Although P and K levels in the soil were still favourable (Table 4 and 5), the increase in leaf nutrient deficiencies provides circumstantial evidence that nutrient availability was reduced in the 1990s as compared to the 1980s. This may be the result of the soil compaction and acidification.

Changes in soil chemical properties continue if current management strategies remain unchanged but it is not possible to predict at what pace that will happen. It is likely that the P and K content of the soil continue to decrease since they are not replenished by inorganic fertilizers. Applying these nutrients to maintain favourable levels is, however, only useful if the soil compaction is dealt with. Some lime, when the sugar cane is ploughed-out, may be required to keep the pH at favourable levels (i.e. pH> 5.5). It was found that since 1979 organic matter levels had decreased by about 40% but currently trash-harvesting is practised which is likely to increase soil organic matter (Wood 1991). Such increase affects many soil properties. For example, the pH buffering capacity may increase reducing the acidifying effects of sulphate of ammonia (Hartemink 1998), but it may also reduce the compactibility of the soil by increasing resistance to deformation. The trash-harvesting is therefore an important step to achieve sustainable land management and favours sugar cane yields (Yadav and Prasad 1992).

The risk of soil compaction at the plantation could be reduced if the overhaul equipment had high flotation instead of conventional (small) tyres. Also strip tillage involving smaller tractors and reduced tillage is helpful (de Boer 1997). The topsoil compaction is alleviated when the sugar cane is ploughed out but deep tillage or sub-soiling is required for the subsoil. It is recommended for the Fluvisols but sub-soiling cannot be recommended for the Vertisols as it is likely to result in more compaction (Ahmad 1996). The subsoil compaction in the Vertisols (up to 0.3 m) is possibly one of the only changes in soil properties which is hard to reverse.

There is a cost to these measures that may not directly be compensated for by extra sugar cane. However, the costs to restore degraded soils may be substantially higher than those required maintaining the soil in favourable conditions for sugar cane production.

REFERENCES

AHMAD, N. (1983) Vertisols. In: *Pedogenesis and soil taxonomy. II. The soil orders* (L.P. Wilding, N.E. Smeck and F.G. Hall, Editors). Elsevier, Amsterdam, pp. 91-123.

AHMAD, N. (1984). Tropical clay soils, their use and management. *Outlook on Agriculture* 13: 87-95.

AHMAD, N. (1996). Management of Vertisols in rainfed conditions. In: *Vertisols and technologies for their management.* (N. Ahmad and A. Mermut, Editors). Elsevier, Amsterdam, pp. 363-428.

ANDERSON, D. L. and **BOWEN, J. E.** (1990). *Sugarcane nutrition.* Potash & Phosphate Institute, Norcross.

BAIN, J.H.C and **MACKENZIE, D.E.** (1975) *Explanatory notes geological series 1:250,000. Ramu - Papua New Guinea.* Australian Government Publishing Service, Canberra.

BLACKBURN, F. (1984). *Sugarcane.* Longman, Harlow

BLEEKER, P. (1983). *Soils of Papua New Guinea.* Australian National University Press, Canberra.

BLOKHUIS, W.A. (1980) Vertisols. In: *Land reclamation and water management-developments, problems and challenges,* ILRI publication 27, Wageningen, pp 43-48.

BOOKER AGRICULTURE INTERNATIONAL (1979). *Ramu Sugar Ltd, Soil survey report* BAI Ltd, London

BOOKER AGRICULTURE INTERNATIONAL (1987). *Final report soil management at Ramu Sugar Ltd.* BAI Ltd, London.

BOUWER, H. (1986). Intake rate: cylinder infiltrometer. In: *Methods of soil analysis, part 1*, physical and mineralogical methods, 2nd edition, ASA-SSSA, Madison, pp 825-844.

CHARTRES, C.J. (1981). Land resource assessment for sugarcane cultivation in Papua New Guinea. *Applied Geography*, 1: 259-271.

DE BOER, H.G. (1997). Strip tillage in sugar cane agriculture: techniques and challenges. *Zuckerindustrie*, 5: 371-375.

DE GEUS, J. G. (1973). *Fertilizer Guide for the Tropics and Subtropics.* Centre d'Etude de l'Azote, Zurich.

EASTWOOD, D. (1990). Ramu stunt disease, development and consequences at Ramu Sugar Ltd *Sugarcane* 2, 15-19.

FAO-UNESCO (1988). *Soil map of the world, revised legend. World soil resources report 60.* Technical paper 20. ISRIC, Wageningen

FAUCONNIER, R. (1993) *Sugar Cane.* CTA/Macmillan, London.

HARTEMINK, A.E. (1998). Acidification and pH buffering capacity of alluvial soils under sugarcane. *Experimental Agriculture*, 34: 231-243.

HARTEMINK, A.E. and **KUNIATA, L.S.** (1996). Some factors influencing yield trends of sugar cane in Papua New Guinea. *Outlook on Agriculture*, 25: 227-234.

HENTY, E.E. and **PRITCHARD, G.H.** (1988). *Weeds of New Guinea and their control*, 4th edition. Department of Forests, Lae.

HUNSIGI, G. (1993). *Production of Sugarcane*, Theory and Practice. Springer-Verlag, Berlin.

KRISHNAMURTHI, M. (1976). Major aspects of sugarcane production in relevance to Papua New Guinea. In: *Agriculture in the tropics* (B.A.C. Enyi and T. Varghese, Editors). UPNG, Port Moresby.

LAL, R. (1979). Physical characteristics of soils of the tropics: Determination and management. In: *Soil physical properties and crop production in the tropics* (R. Lal and D.J. Greenland, Editors). John Wiley & Sons, Chichester, pp 7-44.

LI, C. S. (1985). Sugar insect pests with special reference to moth borers in the Markham valley, Papua New Guinea. *Mushi* 50, 13-13.

LÖFFLER, E., (1977) *Geomorphology of Papua New Guinea.* CSIRO and ANU Press, Canberra.

LOVELAND, P. J. (1991). *Phosphorus sorption in some tropical soils.* Consultancy report to Ramu Sugar Ltd. Cranfield Institute of Technology, Silsoe.

MALAVOLTA, E. (1994). *Fertilizing for high yield sugarcane,* IPI-Bulletin no. 14. International Potash Institute, Basel.

NELSON, L.E. (1980). Phosphorus nutrition of cotton, peanuts, rice, sugarcane and tobacco. In: *The role of phosphorus in agriculture* (F.E. Khasawneh, E.C. Sample and E.J. Kamprath, Editors). ASA-CSSA-SSSA, Madison, pp. 639-736.

ORLANDO FILHO, J. (1985). Potassium nutrition of sugarcane. In: *Potassium in Agriculture* (R.D. Munson, Editor). ASA-CSSA-SSSA, Madison, pp. 1045-1062.

PARFITT, R.L. and **THOMAS, A.D.** (1975). Phosphorus availability and phosphate fixation in Markham Valley soils. *Science in New Guinea*, 3: 123-130.

POCKNEE, S. and **SUMNER, M.E.** (1997). Cation and nitrogen contents of organic matter determine its soil liming potential. *Soil Science Society of America Journal* 61: 86-92.

PROVE, B.G., DOOGAN, V.J. and **TRUONG, P.N.V.** (1995). Nature and magnitude of soil erosion in sugarcane land on the wet tropical coast of north-eastern Queensland. *Australian Journal of Experimental Agriculture*, 35: 641-649.

ROWELL, D.L. and **WILD, A.** (1985). Causes of soil acidification: a summary. *Soil Use and Management* 1: 32-33.

SZENT-IVANY, J. J. H. and **ARDLEY, J.H.** (1962). Insects of Saccharum spp. in the territory of Papua New Guinea. *Proceedings of the International Society of Sugar Cane Technologists* 11, 690-694.

SOIL SURVEY STAFF (1994). *Keys to soil taxonomy*, 6th edition. U.S. Department of Agriculture. Pocahontas Press Inc., Blacksburg, Virginia.

SRIVASTAVA, S.C. (1992). Sugarcane. In: *IFA world fertilizer use manual* (D.J. Halliday and M.E. Trenkel, Editors). International Fertilizer Industry Association, Paris, pp. 257-266.

TROUSE, A.C. and **HUMBERT, R.P.** (1961). Some effects of soil compaction on the development of sugar cane roots. *Soil Science*, 91: 208-217.

UNGER, P.W. and **STEWART, B.A.** (1988). Conservation techniques for Vertisols. In: *Vertisols: Their distribution, properties, classification and management* (L.P. Wilding and R. Puentes, Editors). SMSS/Texas A&M University, Texas, pp. 165-181.

VAN DER VEER, K. (1937). *Land- en Tuinbouw*. In: Nieuw Guinee - Deel II. (W.C. Klein, Editor). J.H. de Bussy, Amsterdam.

WOOD, A. W. (1991). Management of crop residues following green harvesting of sugarcane in north Queensland. *Soil & Tillage Research* 20, 69-85.

YADAV, R. L. and **PRASAD, S. R.** (1992). Conserving the organic matter contents of the soil to sustain sugarcane yield. *Experimental Agriculture* 28, 57-62.

YATES, R.A. (1978). The environment for sugarcane. In: *Land evaluation standards for rainfed agriculture*. World Soil Resources Report no. 49, FAO, Rome, pp 58-72.

THE RESPONSE OF THREE SWEET POTATO CULTIVARS TO INORGANIC FERTILIZERS ON AN ANDISOL IN THE HIGHLANDS OF PAPUA NEW GUINEA

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ABSTRACT

A experiment is reported in which the response of three sweet potato varieties under farmers field conditions to inorganic fertilizer were examined in Gumine, Simbu Province. Fertilizer treatments were 0, 75 and 150 kg N ha^{-1} applied as urea; 0, 50, 100 kg P ha^{-1} applied as triple super phosphate, and 0, 75 and 150 kg K ha^{-1} applied as muriate of potash. Marketable sweet potato yields were substantially increased due to a significant P x K interaction, indicating that these nutrients were limiting sweet potato production. There was greater P-effect than K but the pattern of interactions was related to a significant inter-varietal difference in their response to added nutrients. The magnitude of response by variety Ongi and to an extent, Tripalangi, to added P and K was greater than variety Spagi. Variety adaptation mechanisms developed to offset pest and disease attack and other environmental stress, could reduce variety vigour and responsiveness to fertilizers. The occurrence of such interaction has implications for future on-farm trial work and proper management of fertilizer in subsistence gardens.

Keywords: *Sweet potato, volcanic ash soils, soil fertility, variety x fertilizer interaction.*

INTRODUCTION

Sweet potato (*Ipomoea batatas* (L) Lam) has a diverse role in the highlands of Papua New Guinea. Firstly, it is the staple for the densely populated highlands and is grown under a wide range of soil and climatic conditions (Bourke 1985). Secondly, it is characterized by large numbers of cultivars (Yen 1974; Bourke 1985) of which only a few (about 5-6) may account for >90% of the planting (Wood 1984); thirdly, crop husbandry differ from planting on small round mounds (Kanua and Levett 1990), flat beds (Kanua and Rangaii 1988), raised compost mounds (Waddell 1972), between *gui's* (Wood and Hump-hreys 1982) to sequential planting and harvesting (Rose 1979). Furthermore, sweet potato varieties available to farmers have been selected to suit different soil situations, and are particularly adapted to low levels of soils nutrients (Kanua and Floyd 1988). Some varieties have shown to be adapted to the marginally fertile volcanic soils (Preston 1990; Floyd *et al.* 1988; Goodbody and Humphreys 1986).

However, evidence is scanty on the behaviour or responsiveness of established local cultivars to changing soil conditions; and whether substantial improvements in soil nutrient status is necessary to improve, or increase the yield of these cultivars, as they are often preferred over introduced varieties (Kanua and Floyd 1988). Such information is essential for the improvement of subsistence agriculture. The experiment reported here was conducted to investigate the responsiveness or the response gradient of three local sweet potato cultivars to N, P and K fertilizers, and was conducted on a marginally fertile volcanic ash soil.

METHODS

Experimental Site

The trial was conducted on a gently slopping (15°) farmer's garden at Boromil village, Gumine District, Simbu Province, PNG.

The site was located on an altitude of 1850 m a.s.l. A mean of 10 years rainfall data at the nearby Gumine Station (McAlpine *et al.* 1975) show

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that on an average, the site receives 2,445 mm of rainfall annually; three quarters of which is expected during the months from October to April.

For the Simbu Province, the only published temperature data are for Kundiawa. In an attempt to broaden the data base, Humphreys (1984) used other data from schools in the Province and compared them with data from Kundiawa (1550 m) and Pindaunde (3580 m). He reported mean minimum and maximum monthly temperature range from 13.3 to 26.6°C respectively, with little variation between months. The calculated lapse rate for every 100 m gain in altitude in the Simbu Province is a temperature decline by 7.4 and 5.6°C, mean maximum and mean minimum respectively.

The Soil

The soil was typically volcanic ash in origin. The topsoil was friable and coarse structured, dark brown in color merging into a light brown to yellowish orange subsoil. Two soil samples were collected, one composite sample for the upper and the other for the lower end (Table 1) and sent to the National Chemistry Laboratory in Port Moresby for analysis. The analytical data given in Table 1, indicates that the test soil is strongly acid with P and K being at low levels, whereas P-retention is very high.

Soil fertility is slightly lower on the upper slopes (BS 43%), probably due to erosion of topsoil than the lower slope (BS 51%). Coupled to this, the site had a long history of continuous cultivation with short (12-18 months) fallow breaks. The levels of N are adequate but there is a clear imbalance between Mg and K.

Although interpretation of soils data is often difficult due to large soil variability, the present data indicate that:

Table 1. **Soil physical and chemical data with climatic and environmental descriptions of the experiment site.**

Location		**Gumine**	
Altitude (m)		1850	
Mean annual rainfall (mm)		2445	
Mean temp (°C)	max.	26.6	
	min.	13.3	
Site history		Continuous cultivation with short grass fallow previous <1y	
Soil type		Airfall volcanic ash	
		Lower slope	Upper slope
pH H_2O		5.2	5.2
P (mg/kg)		3	1
exchangeable cations (cmol/kg)			
Ca		4.6	4.1
Mg		3.65	3.35
K		0.20	0.20
Na		0.10	0.10
CEC		16.9	17.9
B.S. %		51	43
Org. Carbon (%)		7.3	7.9
N%		0.52	0.58
C/N Ratio		14	14
P Retention %		96	93

Methods used: Organic matter - Dichromate oxidation; Extractable phosphate - Saunders method, Extractable cations - Neutral, 1 M ammonium acetate; CEC - sum of exchangeable bases and acidity.

1) due to the acid nature of the soil, the availability of micro-nutrients, especially Boron and Molybdenum may be below.

2) The problem of K deficiency is partially induced by the high Mg/K imbalance (ratio > 18) in the soil exchange complex, and partially by K fixation (Kanua 1995). The application of K is only necessary to offset the imbal ance (Mg/K) for a response.

3) The high phosphate fixation (>90%) is a characteristic of soils with volcanic ash influence. This means that the application of this nutrient together with other cations in low supply are highly likely to give a response.

Experimental Design

The experimental areas were cleared of vegetation, cultivated by hand to produce suitable tilth before the plots were marked out.

A split-plot design was used in which three (3) levels of nitrogen, phosphorus and potassium were randomly applied to the main plots which measured 27 m^2. The fertilizer rates were:

N 0, 75 and 150 kg ha^{-1}
P 0, 50 and 100 kg ha^{-1} applied as triple super phosphate,
K 0, 75 and 150 kg ha^{-1} applied as muriate of potash.

The sub-plots measured 9 m^2, and they were randomly allocated to three local sweet potato cultivars, namely Ongi, Tripalangi and Spagi.

The 27 treatments were arranged in randomized complete blocks and replicated three times. The plots were marked out and fertilized before small round mounds (1 m^2) were made in the traditional manner. Immediately after mounding, three sweet potato cuttings of the respective cultivars, approximately 30 cm in length were planted on the mounds at a plant population of 30,000 ha^{-1}. The sweet potato cuttings were collected from gardens in the vicinity of the experiment site. During growth, no plant protection measures were taken other than keeping the crop relatively weed free.

At harvest, mounds were broken up and the yields separated as fresh weight of vines, stockfeed tubers (tubers <100 g) and marketable tubers (>100 g) were recorded for each treatment. Numbers of vines, stockfeed and marketable tubers were also recorded. The trial was planted on the 23rd of January 1987 and harvested after eight months.

Statistical Analysis

The data collected were analyzed by the analysis of variance method after Little and Hills (1978), and treatment means compared by the Duncan's Multiple Range Tests (DMRT).

***Table* 2. Fertilizer effect on the fresh weight yield of marketable tubers averaged over the three sweet potato varieties tested.**

Mean yields (t ha^{-1})[1]						
	N (kg ha^{-1}) fertilizer			K (kg ha^{-1}) fertilizer		
P (kg ha^{-1}) fertilizer	0	75	150	0	75	150
0	4.4b	2.0b	1.9c	1.4b	3.4c	5.3b
50	9.5a	15.0a	16.6b	5.2a	12.9b	17.0a
100	11.6a	13.1a	14.9b	5.1a	16.7a	17.7a

[1] Average of 3 replicates. Means in any column followed by the same letter are not significantly different ($P<0.05$) from each other according to DMRT. LSD (0.05) value for comparing fertilizer (N and K) means in a row is 3.4 t ha^{-1}.

Table 3. **Variety x fertilizer (N, P) effects on marketable tuber yield of sweet potato varieties Ongi, Tripalangi and Spagi.**

Mean yields (t ha^{-1})[1]						
Variety	P (kg ha^{-1}) fertilizer			K (kg ha^{-1}) fertilizer		
	0	50	100	0	75	150
Ongi	5.5a	15.5a	16.5a	5.6a	15.1a	16.8a
Tripalangi	2.0b	12.9a	14.5a	3.8a	11.5b	14.2a
Spagi	0.9b	6.7b	8.5b	2.4a	6.4c	7.2b

[1] Average of 3 replicates. Means in any column followed by the same letter are not significantly different ($P<0.05$) from each other according to DMRT. LSD (0.05) value for comparing fertilizer (P and K) means in a row is 2.4 t ha^{-1}.

RESULTS

Marketable tuber yield was considered sufficient to use as the single relevant indicator of variety response to inorganic fertilizer in this trial. Table 2 gives N x P and P x K effects on mean fresh weight yield of marketable tubers of the three sweet potato varieties tested.

Application of N in the absence of applied P decreased yield. Similarly, increasing K-levels in the absence of P, there was no significant increase on yields above the control. Application of P in the absence of both N and K significantly increased yields.

In general, increasing P with a corresponding increase in K rates gave better yields; hence highest yields were achieved at the highest P and K levels. The variety x fertilizer (P and K) main effects on the marketable tuber yield is given in Table 3. The results indicated significant inter-variety differences in their response to different levels of fertilizer application. Overall, cultivars Ongi and Tripalangi responded more to inorganic fertilizer than Spagi. Cultivar Ongi was the better variety, but its yield was not significantly different from the yields of Tripalangi at the 50 and 100 kg P ha^{-1} and 150 kg K ha^{-1} (Table 3). Ongi out yielded Spagi but at no level of P and/or K (except at zero K) was the yield of Ongi not significant or similar to the yield of Spagi. Cultivar Tripalangi's yield was only significantly different from Spagi's at the 50 and 100 kg P ha^{-1} and 75 and 150 kg K ha^{-1}.

Overall, variety yields were significantly improved due to P fertilizer. The application of P significantly improved yields of cultivars Ongi and Tripalangi but had limited effect on variety Spagi. The statistical analysis did not reveal a variety effect due to nitrogen fertilization. This is probably because of the high levels of organic matter, which provides ample mineralised N to the soil during the cropping period.

DISCUSSION

The significant yield response to added fertilizer suggests that inadequate levels of major elements in the Gumine soils are a constraint to sweet potato production. In particular, inadequate P and K seem to be the critical limiting factors. This results agree with the findings of Floyd *et al.* (1988) on volcanic soils in the Southern Highlands. Furthermore, the evidence for N x P and P x K interaction on the yield of sweet potato is of practical significance. The evidence for a limited N x P interaction is attributed largely to P being probably more limiting on this soil than N as indicated by the soil analytical data (Table 1). This is clearly demonstrated at the highest level of P and altering N levels, there are no significant yield increases due to increasing N levels (Table 2).

In general, the significant P x K interaction is of practical importance, implying that applying P without K can be wasteful resulting in lower yields.

The results indicate that there can be significant differences in variety responses to added fertilizer. The experimental data showed that the yield of cultivar Ongi, followed by that of Tripalangi were significantly improved due to increasing P and K levels. Cultivar Spagi showed some response to P, but was generally inefficient in utilizing added fertilizer.

No explanation for the differences in variety responses to fertilizer can be offered by the experimental data. The reduced response of variety Spagi to fertilizers represents an example of cultivars that are prevalent in farmers fields. A number of factors could be causing this, one of which is probably an adaptation mechanism developed by certain cultivars in this environment which have been continuously used in marginal soils (e.g. Kanua and Floyd 1988) and overly stressed agricultural systems (e.g. Wood 1984). The other reasons could be due to the involvement of diseases, especially viruses (Waller 1985) and nematodes (Bridge and Page 1984). These interacting factors in the ecosystem, coupled with the longer history of domestication of variety Spagi, will act as agents of natural selection pressure on the variety, and consequently reduce the variety vigor. On similar soil types elsewhere in the highlands, Kanua and Floyd (1988) reported that established local varieties of sweet potato were less responsive to differences in yield potential between sites than newly introduced cultivars.

CONCLUSION

Some care is needed in deriving conclusions as the involvement of pests and diseases including nematodes could play a part in these experiments. It is concluded that volcanic soils in Gumine cannot sustain heavy sweet potato yields due to low nutrients, particularly deficient P and K. However, results from this study showed that the deficiencies can be corrected, and sweet potato yields can be increased significantly by applying small amounts of fertilizer.

In this soil, the application of N, P, or K alone is unlikely to bring about a significant response. Results show that these elements must be applied together. There was a greater P effect, which suggests that the inter-play of local mycorrhiza (Floyd *et al.* 1988) in the nutrition of sweet potato cannot be ruled out. Further research is required to strike the right balance between fertilizer and local mycorrhiza interactions to achieve maximum yields. Experimental evidence also showed that sweet potato varieties differ in their responsiveness to increased soil fertility.

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REFERENCES

BRIDGE, J. and **PAGE, S.L.J.**, (1984). Plant Nematodes of Papua New Guinea: their importance as crop pests. Report of a plant nematode survey in Papua New Guinea, 18 October - 20 December 1982. Commonwealth Institute of Parasitology, St. Albans, Herts, U.K. 91 pp.

BOURKE, R.M., (1985). Sweet Potato (*Ipomoea batatas*) production and research in Papua New Guinea. *Papua New Guinea Journal of Agriculture, Forestry and Fisheries*, 33 (3-4): 89-108.

FLOYD, C.N., LEFROY, R.D.B. and **D'SOUZA, E.J.** (1988). Soil fertility and sweet potato production on volcanic ash soils in the Highlands of Papua New Guinea. Field Crops Research, 19:1-25.

GOODBODY, S. and **HUMPHREY, G.S.** (1986). Soil Chemical Status and the Prediction of sweet potato Yields. *Trop. Agric.* (Trinidad), 63 (2): 209-211.

HUMPHREYS, G.S. (1984). The Environment and Soils of Chimbu Province, Papua New Guinea, with Particular reference to Soil Erosion. *Research Bulletin No. 35.* DPI, Port Moresby. 109 pp.

KANUA, M.B, (1995). A review of Properties, nutrient supply, cultivation and management of volcanic soils, with particular reference to Papua New Guinea. *Papua New Guinea Journal of Agriculture, Forestry and Fisheries*. Vol. 38 (2): 102 - 123.

KANUA, M.B and **FLOYD, C.N.** (1988). Sweet Potato Genotype x Environment Interaction in the Highlands of Papua New Guinea. *Trop. Agric.* (Trinidad) Vol. 65 (1): 9-15.

KANUA, M.B. and **LEVETT, M.P.** (1990). An Agronomy Rapid Appraisal Report of the Gumine District of Simbu Province, HAES, Aiyura, Occ. Paper No. 3/90.

KANUA, M.B. and **RANGAII, S.S.** (1988). Indigenous technologies and recent advances in sweet potato production, processing, utilisation and marketing in Papua New Guinea. Discussion Paper 88/5. Department of Agriculture and Livestock, Port Moresby. 20 pp.

LITTLE, T.M. and **HILLS, F.J.** (1978). Agricultural Experimentation. John Wiley and Sons, Inc., New York, USA.

McALPINE, J.R., KEIG, G. and **SHORT, K.** (1975). Climatic Tables of Papua New Guinea. Division of Land Use Research Technology. Paper No. 37. CSIRO, Australia. 177pp.

PRESTON, S.R., (1990). Investigation of compost x fertilizer interactions in sweet potato grown on volcanic soils in the highlands of Papua New guinea. *Trop. Agric.* (Trinidad), 67(3):239-242.

ROSE, C.J., (1979). Comparison of single and progressive harvesting of sweet potato (*Ipomoea batatas* (L) Lam). *Papua New Guinea Journal of Agriculture, Forestry and Fisheries*. 30 (4): 61-64.

WADDELL, E. (1972). The Mound Builders. Agricultural Practices, Environment and Society in the Central Highlands of New Guinea. University of Washington Press, Seattle. 253 pp.

WALLER, J.M., (1985). Diseases of smallholder food crops in the Southern Highlands of Papua New Guinea. Results of a survey conducted in September, 1984. Technical Report 85/series. Department of Primary Industry, Konedobu, NCD, Papua New Guinea.

WOOD, A.W. (1984). Soils. pp 35-54. In: *Agriculture and Nutritional Studies on the Nembi Plateau*, Southern Highlands. Department of Geography Occ. Paper No. 4. (New Series). B. J Allen (Ed). University of Papua New Guinea and Southern Highlands Rural Development Project. Port Moresby.

WOOD, A.W. and **HUMPHREYS, G.S.** (1982). *Traditional Soil Conservation in Papua New Guinea*: Implications for today. IASER Monograph 1b.L. Morauta; J. Pernatta and W. Hearney (Eds). Institute of Applied Social and Economic Research, Port Moresby.

YEN D.E. (1974). The Sweet Potato and Oceania. Honolulu: *Bishop Museum Bulletin*. 236 pp.

EROSION AND SOIL FERTILITY CHANGES UNDER LEUCAENA INTERCROPPED WITH SWEET POTATO IN THE LOWLANDS OF PAPUA NEW GUINEA

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ABSTRACT

Surface runoff, erosion and changes in soil fertility were measured under Leucaena leucocephala *intercropped with sweet potato and compared to sole* Leucaena leucocephala *cropping. The study was conducted on-farm in the humid lowlands of Papua New Guinea for two years (1992-1993 and 1993-1994). The soil at the site was derived from intrusive igneous rocks (Inceptisol) and had a slope of 58%. In the intercropped plots (150 m^2 each) during the two years of observation, surface runoff was 817 and 1003 mm yr^{-1}, or 37% and 55% of the total rainfall. Erosion was low and on average 3.9 and 2.9 t soil ha^{-1} yr^{-1}. Under sole leucaena, surface runoff was 537 and 668 mm yr^{-1} and erosion was 3.5 and 2.2 t soil ha^{-1} yr^{-1}. Linear regression showed that both monthly rainfall and surface runoff, and surface runoff and erosion were well correlated (r^2 >0.6) for intercropped and sole leucaena. Soil fertility declined under intercropped and sole leucaena but there were no major differences. There were also no statistical differences in the height of the leucaena. Sweet potato yields declined from 4.2 t fresh weight ha^{-1} at the first harvest to 0.2 t ha^{-1} after 23 months in the intercropped plots. The study has shown that intercropping leucaena with sweet potato during the first two years does not significantly increase erosion or affect the soil fertility as compared to sole leucaena.*

Keywords: *surface runoff; erosion; soil fertility changes; sweet potato; intercropping;* Leucaena leucocephala.

INTRODUCTION

About 75% of Papua New Guinea is covered with forest of which more than half is on steepland (McAlpine and Quigley 1995). Deforestation by logging, mining, agricultural projects and shifting cultivation is proceeding rapidly and annually about 113,000 ha of forest are cleared (FAO 1990). Much of the forest clearings is required for the expansion of agricultural land. Reforestation, required to avoid irreversible land degradation, occurs at a much slower pace and recent estimates are 1,500 ha yr^{-1} (FAO 1990).

For smallscale farmers who are to a large extent responsible for the deforestation, there are little incentives to plant trees as it reduces their cropping area and they may have to wait for a long time before an economic return can be expected. A partial solution to this problem is the planting of food or cash crops in between rows of trees during the first years which may give some return to the investment of planting trees. This has been practised in many parts of the tropics for a long time and it is usually referred to as the taungya system (Nair 1993). A second incentive is that trees such as *Leucaena leucocephala* can have multiple use. They supply animal feed and wood for timber, pulp or fuel and the mulch can be used for soil improvement. Furthermore *Leucaena* planted on the contour may assist in soil conservation. Planting sweet potato, which is the major starch crop in the lowlands of Papua New Guinea (Allen *et al.* 1995), between rows of *Leucaena* is therefore an attractive land-use system as it produces food and products of the tree. The planting of *Leucaena* trees

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may save further clearing of the forest and reduce land degradation by erosion and the loss of nutrients (Sanchez 1995).

For Papua New Guinea, little is known on the effect of sweet potato and *Leucaena* on soil erosion and the chemical fertility. Therefore an experiment was started in May 1992 with the following objectives: (i) to quantify runoff and erosion in intercropped and sole *Leucaena* plots, (ii) to determine changes in soil chemical properties, (iii) to assess sweet potato yields and the growth of *Leucaena*. The experiment was conducted in the lowlands near Lae in an area were selective logging is followed by the encroachment of small scale farmers. The experiment lasted for two years during which the *Leucaena* trees were not pruned.

MATERIALS AND METHODS

Study area

The study was conducted on-farm near Hobu Community School (6°34'S, 147°02'E) approximately 20 km northeast of Lae at the footslopes of the Saruwaged range. Altitude of the experimental site was 440 m a.s.l. which is considered as lowlands in the agro-climatic classification of Papua New Guinea (Gurnah 1992). Detailed climatic data are not available for the study area. The experiment was situated in an area with high annual rainfall and mean temperatures over 25°C with only slight variations during the year. Annual evaporation (US Class A pan) is about 1500 to 2000 mm (McAlpine *et al.* 1982). The climate is classified as Af (Köppen), a tropical rainy climate with the driest month having over 60 mm of rain.

Slope at the experimental site is 58%. The soils are derived from a mixture of igneous rocks, and are classified as a Typic Eutropepts (Soil Survey Staff 1994) or Eutric Cambisol (FAO-Unesco 1988). Some chemical and physical properties of the soils are presented in Table 1.

The soils have a moderate to slightly acid soil reaction and fair levels of total N and exchangeable cations. Available P levels are low. Effective rooting depth is over 1.2 m. Landslides occasionally occur in the area and are triggered off by earthquake activity after periods of heavy rain (Bleeker 1983).

The natural vegetation in the area is similar to the lowlands and submontane forest in the region. The dominant canopy is formed by *Pometia* sp., *Syzygium* sp. and *Eleocarpus* sp. whereas *Canarium* sp., *Neonauclea* sp., *Dracontemelon* sp., *Dysoxylum* sp., and *Chisocheton* sp. form the co-dominant canopies. (J. Simaga pers. comm.). Areas which have been frequently burned are predominantly under grasslands consisting of *Themeda* sp., *Imperata* sp. and *Saccharum* sp.

Experimental set-up

The experimental site was an abandoned garden previously planted with a mixture of sugarcane, taro, bananas, and sweet potato. The vegetation was cleared in May 1992 followed by burning in June 1992. Four plots of 15 x 10 m each were laid out as a randomized complete block design. At the side and upper boundaries of each plot, a 15 cm

***Table 1.* Some chemical and physical properties of the soils at the experimental site[1].**

Sampling depth(m)	pH H_2O (1:5)	Organic C (g kg^{-1})	Total N (g kg^{-1})	Avail. P (Olsen) (mg kg^{-1})	CEC pH7 (mmol$_c$kg^{-1})	Exchangeable cations (mmol$_c$kg^{-1})			Particle size fractions (g kg^{-1})		
						Ca	Mg	K	sand	silt	clay
0-0 10	6.2	27.9	2.4	5.6	289	267	92	10.2	570	260	170
0. 10-0.26	6.2	28.6	2.6	2.5	276	236	95	9.6	570	200	230
0.26-0.40	6.2	13.2	1.3	0.6	292	223	106	5.5	490	190	320
0.40-0.69	5.6	7.7	0.8	0.3	194	221	107	1.7	480	240	280
0.69-0.91	5.4	8.2	1.2	0.4	66	231	104	2.2	510	180	320
>0.91	5.5	6.8	0.8	0.5	33	234	99	2.2	510	160	330

[1] Data from pit samples taken on 05-04-1996 in a nearby field under fallow vegetation

zinc strip was placed 8 cm into the soil. At the lower end of the plots, a PVC gutter and boxes were installed for the collection of surface runoff and sediment. The collection devices were capable of containing the entire volume of runoff and erosion from one week. In June 1992, all four plots were planted with six months old *Leucaena leucocephala* seedlings at a spacing of 2 x 2 m (37 trees per plot). Two plots were intercropped with sweet potato (*Ipomoea batatas* L.) at 0.5 m x 0.5 m spacing (600 plants per plot).

Data collection and analysis

From 1992 to 1994 runoff and erosion were measured weekly from the collection boxes. Sediment samples were taken to the laboratory, airdried and weighed. Rainfall was measured daily using a standard rain gauge in an open area near the study site. For the presentation of the data, daily rainfall, weekly surface runoff and erosion were accumulated for each month and averaged for the two plots. The first sweet potato was planted with the *Leucaena* in June 1992. Sweet potato tubers were harvested every four months and fresh yield was determined. Planting of sweet potato cuttings was done immediately after the harvest. In total five crops of sweet potato were grown. Weeding was done manually each month in the intercropped plots and every two months in the sole *Leucaena* plots. The height of all *Leucaena* trees was measured at 6, 7, 8, 10, 13 and 18 months after planting.

The soils of each plot were sampled (0-0.15 and 0.15-0.45 m depth) at the beginning of the experiment prior to the burning of the vegetation, and at 2, 12 and 25 months thereafter. Samples were composites of nine locations within each plot. Soils were analyzed at the National Analysis Laboratory in Lae for the following properties: pH water (1:5), total N (Kjeldahl), available P (Brayl) and exchangeable Ca, Mg and K (1*M* NH_4OAc at pH 7). Samples from the soil pit (Table 1) were analyzed at the National Chemistry Laboratory in Port Moresby.

Monthly rainfall, surface runoff and erosion were skewly distributed and the data were log-transformed before regression analysis (Mead *et al.* 1993). Regression analysis was carried out using Statistix ver. 4.1 software. Standard errors of soil chemical properties and analysis of variance of the height of *Leucaena* were also calculated with Statistix software.

RESULTS

Runoff and erosion

During the first year, surface runoff for the intercropped plots was 817 mm and 537 mm for the sole *Leucaena* plots which was equivalent to 37% and 24% of the total rainfall. Surface runoff in the second year was 1003 mm and 668 mm for the intercropped and sole *Leucaena* plots respectively (Table 2). In the second year surface runoff was relatively higher and 55% and 36% of the total rainfall for the intercropped and sole *Leucaena*. The difference in runoff of intercropped and sole *Leucaena* was significant ($P<0.05$).

Surface erosion was 3.9 t ha^{-1} from the intercropped plots and 3.5 t ha^{-1} from the sole *Leucaena* plots during the first year. Erosion decreased to 2.9 t ha^{-1} in the intercropped plots and to 2.2 t ha^{-1} under sole *Leucaena* in the second year despite the relative higher surface runoff. The difference in erosion between intercropped and sole *Leucaena* was not

***Table 2.* Surface runoff and erosion under intercropped and sole *Leucaena*.**

	rainfall (mm)	intercropped		sole *Leucaena*	
		surface runoff (mm)	erosion (t ha^{-1})	surface runoff (mm)	erosion (t ha^{-1})
August 1992-July 1993	2212	817	3.9	537	3.5
August 1993-July 1994	1833	1003	2.9	668	2.2
mean	2023	910	3.4	603	2.9

Figure 1. **Relation between rainfall and runoff (A), and runoff and erosion (B) in intercropped and sole *Leucaena* plots. (All axis on log scales).**

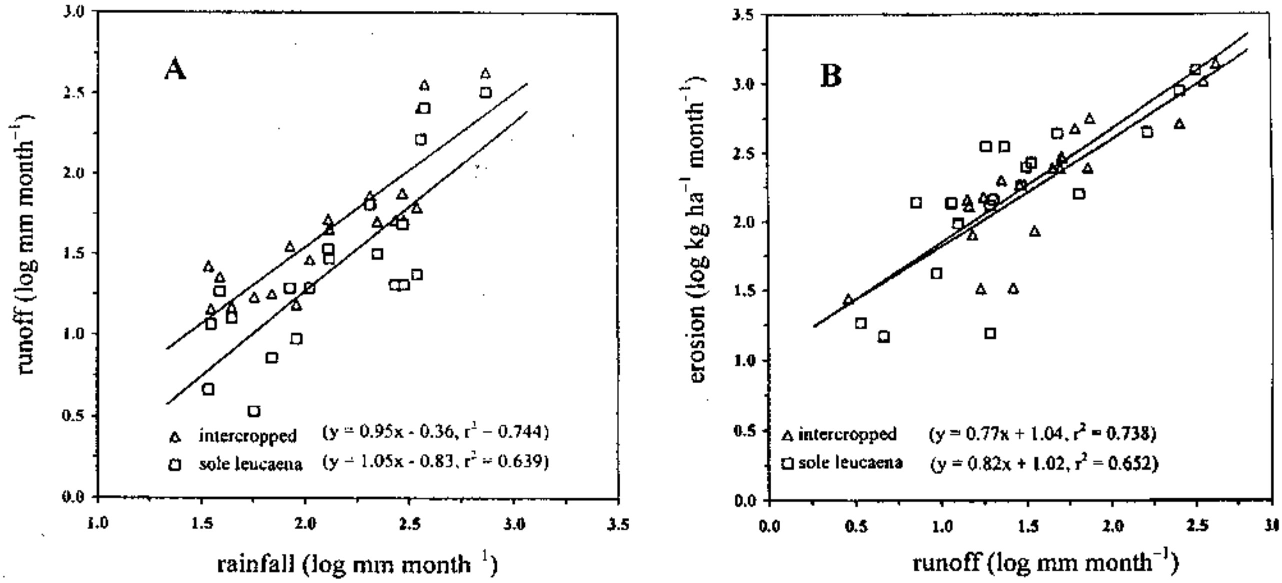

Table 3. **Soil chemical properties of intercropped and sole *Leucaena* at different sampling times.**

		intercropped					sole *Leucaena*				
months after *Leucaena* planting	depth (m)	-1	+2	+12	+25	SED[a]	-1	+2	+12	+25	SED[a]
pH H_2O (1:5)	0-0.15	6.0	5.8	5.7	5.6	0.07	6.2	5.9	5.7	5.8	0.09
	0.15-0.45	5.9	5.3	5.7	5.4	0.12	5.9	5.7	5.3	5.5	0.11
Total N (g kg^{-1})	0-0.15	4.8	2.8	3.3	3.5	0.4	3.6	3.8	4.0	3.7	0.2
	0.15-0.45	1.8	1.6	2.0	1.7	0.1	1.8	2.3	0.6	2.5	0.3
Available P (Brayl)	0-0.15	9	11	8	5	1.5	9	10	5	3	1.2
(mg kg^{-1})	0.15-0.45	2	6	3	1	0.8	4	6	3	<1	0.8
Exchangeable Ca	0-0.15	305	270	320	320	11	265	280	285	300	21
(mmol$_c$ kg^{-1})	0.15-0.45	230	230	280	270	11	210	295	270	270	13
Exchangeable Mg	0-0.15	82	80	67	68	6	78	60	89	84	5
(mmol$_c$ kg^{-1})	0.15-0.45	84	84	58	66	8	85	58	95	76	8
Exchangeable K	0-0.15	5.5	5.5	4.1	2.6	0.9	6.5	4.0	4.0	3.6	0.5
(mmol$_c$ kg^{-1})	0.15-0.45	2.0	1.5	1.5	1.2	0.3	2.0	1.5	1.7	1.8	0.1

[a] Standard error of the difference in means (7*df*).

significant (P=0.17).

In the intercropped plots, erosion per mm of surface runoff was 0.0047 t ha^{-1} in the first year and 0.0028 t ha^{-1} in the second year whereas under sole *Leucaena* this decreased from 0.0065 to 0.0032 t ha^{-1} per mm of surface runoff.

Rainfall-runoff-erosion

Monthly surface runoff and rainfall were well correlated for both treatments (Figure 1). The same amount of monthly rainfall resulted in more runoff in the intercropped plots, but the slopes of the regression equations suggest that higher rainfall resulted in relative more runoff in the sole *Leucaena* plots. About 74% and 64% of the variation in monthly runoff in the intercropped and sole *Leucaena* plots respectively, could be explained by rainfall.

Likewise, monthly surface runoff and erosion were correlated. The slope and y-intercept were approximately the same for intercropped and sole *Leucaena* plots. About 74% of the variation in monthly erosion in the intercropped and 65% in the sole *Leucaena* plots was due to the runoff.

Changes in soil chemical properties

The pH of the top and subsoil of both the intercropped and sole *Leucaena* plots, decreased significantly with time (P=0.05) and the decrease was 0.4 to 0.5 unit (Table 3). Total nitrogen decreased in the topsoils of the intercropped plots but did not change significantly in the subsoils. Under sole *Leucaena*, total nitrogen decreased in the subsoil whereas no changes were found in the topsoils. Available phosphorus decreased in the topsoils under intercropped and sole *Leucaena* to low levels. Subsoil phosphorus increased between the first and second sampling but decreased to a very low level at 12 and 25 months after the *Leucaena* planting. No significant changes were found in the topsoil exchangeable calcium levels but subsoil calcium levels increased under both intercropped and sole *Leucaena*. Initial exchangeable magnesium levels under intercropped and sole *Leucaena* were not significantly different from 25 months thereafter. Exchangeable potassium was significantly lower at 25 months than the initial sampling for both top and subsoils of the intercropped and sole *Leucaena* plots.

Leucaena ***growth and sweet potato yield***

There were no statistical differences (P>0.05) in the height of *Leucaena* when intercropped or grown as a sole crop. Three months after planting, the *Leucaena* trees were about 0.5 m but one year later the trees were 4.3 m in the intercropped and 5.3 m in the sole *Leucaena* plots (Table 4).

Table 4. **Height (m) of intercropped and sole** ***Leucaena*** **(±1 standard deviation)**

age (months)	Intercropped		sole *Leucaena*	
9	0.51	±0.24	0.59	±0.21
10	0.75	±0.29	0.79	±0.28
11	1.32	±0.43	1.60	±0.26
13	1.76	±0.49	2.21	±0.81
16	3.31	±0.79	3.89	±0.71
21	4.34	±1.09	5.28	±1.35

Yields of sweet potato decreased with time. The first crop harvested at four months yielded 4.2 t ha^{-1} (fresh tuber weight), followed by 3.9 t ha^{-1} (9 months), 2.7 t ha^{-1} (14 months) and 2.2 t ha^{-1} at 19 months after the *Leucaena* planting. The fifth and last planted crop was harvested at 23 months and yielded only 0.2 t ha^{-1}.

DISCUSSION

Surface runoff and erosion from the intercropped plots was on an average 307 mm yr^{-1} and 0.5 t ha^{-1} yr^{-1} higher than under sole *Leucaena*. This is probably due to the higher frequency of weeding and the harvest operations in the intercropped plots. Similar observations were made by Kijkar (1985) who also found higher surface runoff and erosion from teak plots.

It was found that surface runoff was relatively higher in both intercropped and sole *Leucaena* plots in the second year, but that did not result in more erosion. The closing canopies of the *Leucaena* reduced splash erosion but infiltration was apparently also reduced. This is contrary to what is commonly found (e.g. Young 1989; Sanchez 1995) and hitherto not fully understood.

Average erosion from the intercropped plots was below 4 t ha^{-1} yr^{-1}. Such erosion rates were also obtained in fallow plots with the same slope in Chimbu Province (Papua New Guinea) whereas erosion rates of 13.6 t ha^{-1} yr^{-1} were recorded from sweet potato gardens in the Southern Highlands (Bleeker 1983). Erosion under both intercropped and sole *Leucaena* was below the FAO's acceptable lower limit of 10 t ha^{-1} for water-induced erosion (FAO 1978). Young (1989) mentioned that erosion rates of 2 to 10 t ha^{-1} yr^{-1} are moderate and also Lal (1994) considers that erosion rates below 5 t ha^{-1} yr^{-1} are slight.

Levels of plant nutrients decreased under both intercropped and sole *Leucaena*. The decrease is possibly the result of nutrient uptake by the *Leucaena* and the sweet potato. Part of the decline in nutrients may have been caused by the loss of topsoil as such loss may have major soil fertility implications (Sanchez 1995; Zöbisch *et al.* 1995).

Sweet potato yields decreased with time and four crops with yields of 2.2 to 4.2 t ha^{-1} could be grown between the *Leucaena* before competition for water, nutrients and solar radiation decreased yield levels below 0.5 t ha^{-1}. Overall yields were low and confirm the data from Louman and Hartemink (1998).

CONCLUSIONS

Intercropping *Leucaena* with sweet potato resulted in slightly higher surface runoff and erosion as compared to sole *Leucaena* but levels of erosion were very low in both treatments (< 4 t ha^{-1} yr^{-1}). Changes in soil fertility were similar in intercropped and sole *Leucaena* plots. The study has shown that intercropping *Leucaena* with sweet potato during the first two years does not significantly increase erosion, affect soil fertility and the growth of *Leucaena* as compared to sole *Leucaena* cropping.

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REFERENCES

ALLEN, B.J., BOURKE, R.M. and **HIDE, R.L.** (1995). The sustainability of Papua New Guinea agricultural systems: the conceptual background. *Global Environmental Change* 5:297-312.

BLEEKER, P. (1983). Soils of Papua New Guinea. ANU Press, Canberra.

FAO (1978). Report on the FAO/UNEP Expert Consultation on methodology for assessing soil degradation. FAO, Rome.

FAO-UNESCO (1988). Soil map of the world, revised legend. World soil resources report 60, FAO, Rome.

FAO (1995). Forest resource assessment 1990, global synthesis. FAO, Rome.

GURNAH, A.M. (1992). Agro-climatic zones of Papua New Guinea. *Niugini Agrisaiens* 1:17-22.

LOUMAN, B. and **HARTEMINK, A.E.** (1998). Sweet potato production in hedgerow intercropping systems in the lowlands of Papua New Guinea. *Papua New Guinea Journal of Agriculture, Forestry & Fisheries* 41:91-98 (This issue)

KIJKAR, S. (1985). Effects of highland agroforestry on soil conservation and productivity in Northern Thailand, pp. 75-84. In N.T. Vergara and N.D. Briones (eds.) *Agroforestry in the humid tropics: Its protective and ameliorative roles to enhance productivity and sustainability.*

LAL, R. (1994). Global overview of soil erosion, pp 39-51. In: *Soil and Water Science: Key to Understanding Our Global Environment.* SSSA Special Publication 41, Madison.

McALPINE, J. R., KEIG, G. and **FALLS, R.** (1983). *Climate of Papua New Guinea.* ANU Press, Canberra.

McALPINE, J.R. and QUIGLEY, J. (1995). *Papua New Guinea natural resources, land use and population.* PNGRIS report no. 7, CSIRO, Canberra.

MEAD, R., CURNOW, R.N. and **HASTED, A.M.** (1993). *Statistical methods in agriculture and experimental biology.* Chapman & Hall, London.

NAIR, P.K.R. (1993). *An Introduction to Agroforestry.* Kluwer, Dordrecht.

SANCHEZ, P.A. (1995). Science in agroforestry. *Agroforestry system* 30:5-55.

SOIL SURVEY STAFF (1994). *Keys to soil taxonomy, 6th edition.* USDA-Soil Conservation Service, Pocahontas Press, Blacksburg.

YOUNG, A. (1989). *Agroforestry for soil conservation.* CAB International, Wallingford.

ZÖBISCH, M.A., RICHTER, C., HEILIGTAG, B. and **SCHLOTT, R.** (1995). Nutrient losses from cropland in the Central Highlands of Kenya due to surface runoff and soil erosion. *Soil & Tillage Research* 33:109-116.

SWEET POTATO PRODUCTION IN HEDGEROW INTERCROPPING SYSTEMS IN THE LOWLANDS OF PAPUA NEW GUINEA.

Bas Louman[1] and Alfred E. Hartemink[2]

ABSTRACT

In an experiment in the Morobe Province of Papua New Guinea, sweet potato (Ipomoea batatas) *was grown between* Leucaena diversifolia *and* Acacia auriculiformis *hedgerows (1650 trees ha^{-1}), and as a sole crop. The experiment was conducted at three locations on Entisols and Inceptisols at altitudes below 550 m a.s.l. Sweet potato yields, above ground biomass of the trees, and nutrient contents of the leaf mulch were measured from 1992 to 1994. The hedgerows were coppiced annually. There were no significant differences in sweet potato yields between the intercropped hedgerows and when grown as a sole crop. Average marketable tuber yields were very low and varied from 2.1 to 6.6 t ha^{-1} yr^{-1} (CV%: 27-51%). Biomass (i.e. wood and mulch) production of* Leucaena *and* Acacia *was also low but varied widely between years.* Leucaena *produced significantly more biomass (7.6 t ha^{-1}) than* Acacia *(1.8 t ha^{-1}) only in 1994. The nitrogen concentration of the* Leucaena *leaves (mean 29.5 g kg^{-1}) was higher than of* Acacia *(mean 21.1 g kg^{-1}) but phosphorus concentrations were similar. Potassium and sulphur concentrations were higher in* Leucaena *than in* Acacia *in 1993 and 1994. Due to higher biomass production and higher nutrient concentrations, there were more nutrients returned to the soil with* Leucaena *than with* Acacia *mulch. After three seasons of sweet potato cropping, no statistical differences in soil chemical properties were found. It was concluded that annually coppiced* Leucaena *and* Acacia *hedgerows is attractive for subsistence farmers in areas where wood or fodder is scarce since it is not affecting sweet potato yields.*

Key words: *Sweet potato, hedgerow intercropping,* Leucaena diversifolia, Acacia auriculiformis, *soil fertility, Papua New Guinea.*

INTRODUCTION

Papua New Guinea has a low population density (8.9 km^{-2}) and about 75 to 80% of the land is covered with natural forests (FAO 1995; McAlpine and Quigley 1995). Forests and people, however, are not evenly distributed over the country. Several areas are densely populated with only little or degraded forests remaining by which the availability of firewood is reduced (Louman 1991). In such areas food production is affected and has resulted for example in the replacement of taro (*Colocasia esculenta*) by sweet potato (*Ipomoea batatas*) due to its lower demand on the soil and the greater ease of cultivation (Barrau 1958). Sweet potato is the main staple crop for the majority of the people in Papua New Guinea (Allen *et al.* 1995). Yields are very variable and much depends on the environmental conditions (e.g. altitude, soils, climate), varieties and the system of cultivation (e.g. mounds, plant density). Bourke (1985) listed yield records of subsistence sweet potato gardens in Papua New Guinea and 30 to 50 t ha^{-1} (fresh weight) are obtained in some areas whereas in others yield levels hardly exceed 5 t ha^{-1}.

Yields can be substantially increased by the selection of cultivars (Levett and Osi'lis 1990) and by improved husbandry practices. Bourke (1985) reviewed the literature on fertilizer trials conducted in Papua New Guinea and noted that consistent yield responses to organic fertilizers (i.e. manure, coffee pulp, poultry litter) and inconsistent responses to inorganic fertilizers. For many farmers

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organic fertilizers are not available, and inorganic fertilizers are too expensive or crop response and profitability is poor. One possible way to overcome the lack of organic fertilizers is to grow crops on the farm where biomass can be added to the soil to improve its fertility status. A system which has received considerable attention during the past decade is the hedgerow intercropping or alley cropping system by which food and tree crops are mixed in spatial and temporal arrangements (Sanchez 1995).

Literature on the use of sweet potato in hedgerow intercropping systems is limited and most trials were conducted with maize. Sweet potato is perhaps not a very suitable crop grown between rows of trees because it is sensitive to shading which seriously reduce yields (e.g. Martin 1985; Roberts-Nkrumah *et al.* 1986). Planting trees, which are regularly coppiced in sweet potato gardens, could have benefits outweighing the possible yield loss through shading as the trees may produce fodder or fuelwood which is important in highly populated areas. We therefore conducted an experiment that examined sweet potato yields of a sole crop, and when intercropped between annually coppiced hedgerows of *Acacia auriculiformis* and *Leucaena diversifolia*. The research took place on-farm in the lowlands of Papua New Guinea.

MATERIALS AND METHODS

The sites

The experiment was carried out on three sites: Unitech (University of Technology), Hobu, and Musom in the Morobe Province of Papua New Guinea. Unitech (6°41'S, 146°98'E) is located at an alluvial plain 8 km N of Lae at an altitude of 65 m a.s.l. The experimental site had a slope of 1.5%. Mean annual rainfall is 4420 mm and the rain is evenly distributed throughout the year. Average daily temperatures are 26.3°C with a daily minimum of 22.9°C and a maximum of 29.7°C. Annual evaporation (US Class A pan) is 2140 mm, and rainfall exceeds evaporation in each month (McAlpine *et al.* 1975).

Hobu village (6°34'S, 147°02'E) is located in the Saruwaged mountain range at an altitude of about 440 m a.s.l. The plots at Hobu were located on a slope of 70%. There are no climatic data available for the site but annual rainfall is probably lower than at Unitech and between 1800 and 2500 mm (Ford 1974).

Musom village (6°31'S, 146°59'E) is also situated in the Saruwaged range, at an altitude of 550 m a.s.l. At Musom, the experimental plots were lo-

Table 1. **Soil analytical data of selected horizons at the experimental site[1].**

Site	Unitech		Hobu		Musom	
sampling depth (m)	0-0.23	0.42-0.57	0-0.10	0.40-0.70	0-0.26	0.42-0.67
pH H_2O (1.5)	5.9	6.4	6.2	5.6	6.0	5.8
Organic C (g kg^{-1})	24	5	28	8	29	10
Total N (g kg^{-1})	2.0	0.4	2.4	0.8	2.6	0.9
Available P (Olsen) (mg kg-1)	11.5	2.5	5.6	0.3	4.8	4.3
Exchangeable Ca ($mmol_c$ kg^{-1})	232	242	267	221	276	300
Exchangeable Mg ($mmol_c$ kg^{-1})	45	48	92	107	52	85
Exchangeable K ($mmol_c$ kg^{-1})	6.5	1.1	7.0	1.7	16.5	7.2
CEC ($mmol_c$ kg^{-1})	126	35	289	194	434	476
Bulk density (kg dm^3)	1.10	1.11	0.90	n.d.	0.86	n.d.

[1] Data are of samples taken in soil pits in March 1996.
n.d. not determined

cated on a slope of 20%. Climate is probably similar to that of the Hobu site although average temperatures are slightly lower.

Soils

Soils at the Unitech site are derived from alluvial deposits consisting of sedimentary and igneous rocks originating from the Saruwaged mountain range. The soils at Unitech are classified as Entisols or Typic Tropofluvents (Soil Taxonomy). At Hobu and Musom soils have developed in a mixture of colluvial poorly sorted material deposited on igneous rocks. At both sites, the soils were classified as Inceptisols or Typic Eutropepts. Some analytical data of the soils at the three sites are listed in Table 1. Soils at the experimental sites had fair fertility levels with moderately acid soil reactions. Levels of available phosphorus were moderate in the Unitech soils but low at Hobu and Musom.

Experimental Design

Prior to the establishment of the experiment, the block at Unitech was covered with *Imperata* grass and trees, whereas at the Hobu site grass and other weeds dominated the plots. Secondary forest with some coffee trees was dominant at the site in Musom.

The experiment was set up as a randomized complete block design with three replicates and three treatments: (i) sweet potato monocropping, (ii) sweet potato with *Acacia auriculiformis* hedges, and (iii) sweet potato with *Leucaena diversifolia* hedges. The sites at Unitech, Hobu and Musom were treated as a block and each block had three plots of 4.5 m by 12 m. Measurements took place in 1992, 1993 and 1994.

The hedges were planted in June 1991 at 4 m intervals with 1.5 m between the trees (9 trees per plot, 1650 trees ha^{-1}). A first sweet potato crop was cultivated in 1991, but no data were collected. In June 1992, sweet potato cuttings of five local cultivars (kuk, pipi, watu, sakat, and kwimbu) were planted. Two cuttings were planted in mounds with a diameter of 0.75 m and a height of about 0.20 m. Distance between the mounds was 1 m, resulting in 3 rows of sweet potato between the hedges (7500 sweet potato plants ha^{-1}). The sweet potato monocropping plots had a plant density of 10,000 plants ha^{-1}. Weeds were manually uprooted every month but the weeds were not removed from the field. After the harvest of the sweet potato, the plots were left fallow until the next planting season. All crop residues were returned to the plots.

Biomass Sampling

In November and December of each year, the sweet potato was harvested. The fresh weight of sweet potato tubers and vines was weighed in the field and in each plot, five samples of four plants were taken. One tuber of each sample was oven dried at 70°C for the first, and at 105°C for the second 24 h. The fourth and fifth full leaf from the base of the vine were sampled and for each sample 24 leaves were taken for analysis. The leaves were cleaned by dipping them in de-ionized water and dried with tissue before ovendrying at 70°C. After 24 h in the oven, 5 to 6 g of the sample was taken and sent to the National Analysis Laboratory in Lae for analysis of the N,P,K and S content. The remaining leaves were dried for another 24 hours at 105°C for dry weight determination.

Trees were coppiced at 0.4 m above ground level in June of each year and the biomass was determined. The biomass was divided into three categories: (i) leaves and petioles, (ii) branches with a diameter less than 0.02 m, and (iii) branches and stems with a diameter over 0.02 m (firewood). Total fresh weight per plot (9 trees) was determined in the field for each component. Samples of the leaves were taken after thorough mixing and cleaned with a tissue. The samples were ovendried at 70°C and after 24h 5 to 6 g were taken for nutrient analysis. The small branches were cut into 0.1 m lengths, mixed, and a 0.5 kg sample was taken and ovendried. Firewood was cut into 1 m lengths and the 0.1 m base of each 1 m piece was ovendried for dry matter determination.

Soil Sampling and Analysis

At the experimental sites, soil pits were dug in March 1996 and soil samples were taken of each horizon. In addition, the *Leucaena*, *Acacia* and sole sweet potato plot were sampled at Hobu and Musom. In each plot, nine samples of 0-0.15 m depth were taken using an Edelman auger. These were thoroughly mixed whereafter a subsample was taken. All samples were airdried, ground and passed through a 2 mm sieve. Samples were analyzed at the National Analysis Chemistry Laboratory in Port

Moresby. The following methods were used: pH H_2O in 1:5 suspension of soil and water; organic carbon by $K_2Cr_2O_7$ and H_2SO_4 oxidation (Walkley and Black); total N by Kjeldahl; available P by $NaHCO_3$ extraction (Olsen); exchangeable cations Ca, Mg, K, Na and CEC percolation by 1 M NH_4OAc followed by spectrophotometry (K, Na), AAS (Ca, Mg) and titration (CEC).

Statistical analysis

Data on fresh weight of tubers, dry weight of above ground tree biomass and nutrient content of tree leaves were analysed statistically using Minitab (version 8). ANOVA showed no significant differences between the years and the data were subsequently analysed separately for each year. Coefficients of Variance (CV%) are reported for sweet potato yields, whereas student's *t*-tests were used to compare the biomass production of trees and the nutrient content of the leaves

Soil analytical data after three cropping seasons were analyzed by ANOVA using Statistix4.1 software. Standard error for the difference in means is reported.

RESULTS

Biomass production

Statistical analysis revealed no significant differences in sweet potato yields between treatments and years. The *Leucaena* treatment yielded 2.1 to 4.9 t tubers ha^{-1} between 1992 and 1994, whereas yields in the sole sweet potato plots were varying between 2.9 to 6.6 t ha^{-1} (Table 2). Variation was large between the years and within the treatments. It was lowest in 1994 (CV 27%) and in the *Acacia*

***Table 2.* Sweet potato yields of intercropped and sole sweet potato plots from 1992 to 1994 (t ha^{-1} fresh weight).**

	1992	1993	1994	CV%
Leucaena	2.1	4.9	3.1	46
Acacia	3.5	4.1	2.4	39
sole sweet potato	2.9	6.6	3.2	51
CV%	47	46	27	

***Table 3.* Wood and mulch production of *Leucaena* and *Acacia* from 1992 to 1994 (t ha^{-1} dry weight).**

	1992			1993			1994		
	wood	mulch	total	wood	mulch	total	wood	mulch	total
Leucaena	1.0	1.1	2.1	0.8	1.3	2.1	4.9	2.7	7.6
Acacia	0.3	0.8	1.1	0	0.1	0.1	0.5	1.3	1.8
Difference	n.s.	n.s.	n.s.	n.s.	P<0.05	n.s.	P<0.05	n.s.	P<0.05

n.s. not significant

Table 4. **Nutrient concentrations in *Leucaena* and *Acacia* leafs from 1992 to 1994 (mg kg⁻¹).**

Nutrient	Tree	Year 1992	1993	1994
Nitrogen	*Leucaena*	32.2	33.1	23.3
	Acacia	23.3	21.9	18.2
	Difference	P<0.05	P<0.05	P<0.05
Phosphorus	*Leucaena*	2.9	3.5	4.4
	Acacia	3.0	3.1	4.6
	Difference	n.s.	n.s.	n.s.
Potassium	*Leucaena*	13.3	14.4	13.9
	Acacia	10.3	10.4	11.8
	Difference	n.s.	P<0.05	n.s.
Sulphur	*Leucaena*	2.2	1.5	2.2
	Acacia	1.4	0.9	1.5
	Difference	n.s.	P<0.05	P<0.05

n.s. not significant

Table 5. **Nutrient in the tree leaf mulch from 1992 to 1994 (kg ha⁻¹).**

Nutrient	Tree	Year 1992	1993	1994	Total
Nitrogen	*Leucaena*	15	20	38	73
	Acacia	10	1	10	21
	Difference	n.s.	n.s.	P<0.05	P<0.05
Phosphorus	*Leucaena*	1	2	7	10
	Acacia	1	<0.5	2	3
	Difference	n.s.	n.s.	P<0.05	P<0.05
Potassium	*Leucaena*	6	9	23	38
	Acacia	4	1	6	11
	Difference	n.s.	n.s.	P<0.05	P<0.05
Sulphur	*Leucaena*	1	1	4	6
	Acacia	<0.5	<0.5	1	2
	Difference	n.s.	P<0.05	P<0.05	P<0.05

n.s. not significant

treatment (CV 39%).

Large variation was also found in the wood and mulch production of *Leucaena* and *Acacia*. In 1994, *Leucaena* produced significantly more wood than in 1992 or 1993, and it produced more wood than *Acacia* which production was on average less than 0.5 t ha^{-1} yr^{-1} (Table 3).

Mulch production did not differ significantly between *Acacia* and *Leucaena* except in 1993 when Acacia (0.1 t ha^{-1}) produced significantly lower than *Leucaena* (1.3 t ha^{-1}). *Leucaena* produced significantly more biomass than *Acacia* in 1994 only.

Nutrients

Nitrogen concentrations in *Leucaena* leaves were consistently higher than those in *Acacia* leaves (Table 4). In 1994, nitrogen concentrations were lower than in 1993 or 1992 for both *Leucaena* and *Acacia*. Phosphorus concentrations increased significantly in the *Leucaena* leaves between 1992 and 1994. No statistical difference was observed in the phosphorus concentrations between *Leucaena* and *Acacia* leaves. Potassium concentrations of *Leucaena* an *Acacia* did not change between 1992 and 1994. Sulphur concentrations showed a significant decline in 1993 in both tree species. Sulphur concentrations of *Leucaena* leaves were higher than of *Acacia* in both 1993 and 1994.

Due to the higher tree leaf mulch production and the higher nitrogen concentration, there was more nitrogen returned with the mulch of the *Leucaena* than with the *Acacia* in 1994 (Table 5). Overall, significant more nutrients were returned to the soil by the *Leucaena* than by the Acacia mulch. It also seems that total nutrients returned with the *Leucaena* mulch increased over the years but such trend was not found in the *Acacia*. After three seasons of sweet potato cropping there were no significant differences between the soils under *Leucaena*, *Acacia* or sole sweet potato (Table 6).

DISCUSSION

Sweet potato yields ranged from 2.1 to 6.6 t ha^{-1} which are very low but not exceptional low yields for smallholders in the lowlands of Papua New Guinea (Bourke 1985). Sayok and Hartemink (1998 this issue) also found low yield levels of sweet potato in the Hobu area of the Morobe Province. The reasons for the low yield levels are hitherto not fully understood but could be due to the varieties grown.

We expected tuber yields in sole sweet potato plots to be higher due to the absence of shading and the

Table 6. **Topsoil (0-0.15 m) chemical properties after 3 seasons of intercropped and sole sweet potato cultivation[1].**

	Leucaena	*Acacia*	sole sweet potato	SED[2]
pH H_2O (1:5)	5.9	5.9	6.1	0.13
Organic C (g kg^{-1})	37	33	32	8
Total N (g kg^{-1})	3.4	3.0	2.9	0.6
Available P (Olsen) (mg kg^{-1})	4.4	5.3	7.7	4.0
Exchangeable Ca ($mmol_c$ kg^{-1})	264	274	304	40
Exchangeable Mg ($mmol_c$ kg^{-1})	52	72	76	26
Exchangeable K ($mmol_c$ kg^{-1})	13	16	12	8
CEC ($mmol_c$ kg^{-1})	412	390	454	58
Base saturation (%)	81	93	86	6

[1] Data reported are means of soil samples taken at Hobu and Musom in March 1996

[2] Standard error of the difference in means (5 *df*)

25% higher plant density. This was reported from intercropping systems with sweet potato in Rwanda (Balasubramanian and Sekayange 1991) and Sierra Leone (Karim *et al.* 1991). However, in our experiment we found no significant yield differences between sole and intercropped sweet potato. The absence of differences is possibly due to the low yields that apparently cause a high degree of variation (CV: 39 to 51%). There were also no significant yield trends during the years which again may be due to the low yield level with the high associated variability (CV: 27 to 47%).

The amount of mulch (small branches and leaves) produced during 1992 and 1993 by the *Leucaena diversifolia* trees was 1.1 and 1.3 t ha^{-1} respectively. Such mulch production is very low when compared to *L. leucocephala* in West Africa (e.g. Kang *et al.* 1985; Palada *et al.* 1992; Shannon and Vogel 1994) but similar to *L. leucocephala* mulch production in East Africa (Jama *et al.* 1988; Macklin *et al.* 1989). In the New Britain Province of Papua New Guinea *L. diversifolia* produced about 2.3 t dry weight ha^{-1} yr^{-1} (Brook 1992). The low mulch production of the *Leucaena* trees in our experiments may be due to the low plant density (1650 trees ha^{-1}) and psyllid (*Heteropsylla cubana*) damage which was observed during the first three months after coppicing.

Mulch production of Acacia was similar to *Leucaena* except during 1993 because of a dry spell that occurred after coppicing. It is generally found that *Acacia auriculiformis* coppices poorly under dry conditions and preferably coppicing should take place during the wet season (Turnbull 1986). We observed that Acacia trees which survived coppicing, had usually one or more branches remaining below 40 cm. Ryan and Bell (1989) and Turnbull (1986) also found that regrowth of *A. auriculiformis* is better when one living branch is left after coppicing.

Nitrogen concentrations in the *Leucaena* and *Acacia* leaves were similar to those found by other researchers (e.g. Brook 1992; Xu *et al.* 1992; Young, 1989), but lower than the 43 to 44 g kg^{-1} found by Palada *et al.* (1992). Leaf phosphorus concentrations were higher than those found by Brook (1992), whereas potassium concentrations were lower than reported by Brook (1992) and Young (1989).

Significantly more nutrients were returned with the *Leucaena* mulch than with the *Acacia* mulch in 1994. Absolute quantities are, however, low. The low sweet potato yields under *Leucaena* indicate that the nutrient additions with the mulch did not have a significant influence on the yield. It was also found that after three seasons there were no differences in soil fertility between sole sweet potato and the intercropped plots. Apparently, at the current low levels of production, the limited nutrient inputs with mulch and nutrient outputs by the tubers do not have a significant effect on soil chemical properties.

CONCLUSION

At the low external input level in the lowlands of the Morobe Province, annually coppiced hedgerows of *Leucaena diversifolia* or *Acacia auriculiformis* do not affect sweet potato yields. The hedgerows produce fodder and fuelwood, which is beneficial to the farmers.

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REFERENCES

ALLEN, B.J., BOURKE, R.M. and **HIDE, R.L.** (1995). The sustainability of Papua New Guinea agricultural systems: the conceptual background. *Global Environmental Change* 5: 297-312.

BALASUBRAMANIAN, V. and **SEKAYANGE, L.** (1991) Effects of tree legumes in hedgerows on soil fertility changes and crop performance in the semi-arid highlands of Rwanda. *Biological Agriculture and Horticulture* 8: 17-32.

BARRAU, J. (1958) *Subsistence agriculture in Melanesia.* Bernice P. Bishop Museum Bulletin 219. Bishop Museum Press, Honolulu.

BOURKE, R.M. (1985) Sweet potato (*Ipomoea batatas*) production and research in Papua New Guinea. *Papua New Guinea Journal of Agriculture, Forestry and Fisheries* 33: 89-108

BROOK, R. (1992) Early results from an alley cropping experiment in the humid lowlands of Papua New Guinea. *Nitrogen Fixing Tree Research Reports* 10: 73-76

FAO (1995). *Forest resource assessment 1990, global synthesis.* FAO, Rome.

FORD, E. (1974) Climate. In: Ford E (ed) Papua New Guinea resource atlas, pp 8-9. Jacaranda Press, Milton.

JAMA, B., GETAHUN, A., NGUGI, D. and **MACKLIN, B.** (1988) *Leucaena alley cropping for the Kenyan coast.* In: Prinsley RT and Swift MJ (eds) Amelioration of soil by trees, pp 155-172. Commonwealth Secretariat, London

KANG, B.T., GRIMME, H. and LAWSON, T.L. (1985) Alley cropping sequentially cropped maize and cowpea with Leucaena on a sandy soil in Southern Nigeria. *Plant and Soil* 85: 267-277

KARIM, A.B., SAVILL, P.S. and **RHODES, E.R.** (1991) The effect of young *Leucaena leucocepahala* (Lam) De Wit hedges on he growth and yield of maize, sweet potato and cowpea in an agroforestry system in Sierra Leone. *Agroforestry Systems* 16: 203-211.

LEVETT, M.P. and **OSI'LIS, P.** (1990) *Preliminary agronomic evaluation of 383 sweet potato (*Ipomoea batatas *(L.) Lam.) accessions grown on a clayloam soil under wet tropical lowland conditions at Laloki, Central Province.* Technical report 90/4. Department of Agriculture and Livestock, Konedobu.

LOUMAN B. (1991) The possible contribution of social forestry to forest development in Papua New Guinea. *Klinkii* 4: 24-39

MACKLIN, B., JAMA, B., KEDIR, R., and **GETAHUM, A.** (1989) Results of alley cropping experiments with *Leucaena leucocephala* and *Zea maize* at the Kenya coast. *Leucaena Research Reports* 9: 61-64

MARTIN, F.W. (1985) Differences among sweet potatoes in response to shading. *Tropical Agriculture* 62: 161-165

McALPINE, J.C., KEIG, G., and **SHORT, K.** (1975) *Climatic tables of Papua New Guinea.* CSIRO, Canberra.

McALPINE, J.C. and **QUIGLEY, J.** (1995) Papua New Guinea natural resources, land use and population 0 Summary statistics from PNGRIS. PNGRIS Report no. 7, CSIRO, Brisbane.

PALADA, M.C., KANG, B.T. and **CLAASEN, S.L.** (1992) Effect of alley cropping with *Leucaena leucocephala* and fertilizer application on yield of vegetable crops. *Agroforestry Systems* 19: 139-147

ROBERTS-NKRUMAH, L., WILSON, L.A., and **FERGUSON, T.U.** (1986) Response of four sweet potato cultivars to levels of shade: 2. Tuberization. *Tropical Agriculture* 63: 265-270

RYAN, P.A. and **BELL, R.E.** (1989) *Growth, coppicing and flowering of Australian tree species in trials in southeast Queensland, Australia.* In: Boland DJ (ed) Trees for the tropics: growing Australian multi purpose trees and shrubs in developing countries, pp 49-68. ACIAR Monograph 10. ACIAR, Canberra.

SAYOK, A. and **HARTEMINK, A.E.** (1998) Erosion and soil fertility changes under leucaena intercropped with sweet potato in the lowlands of Papua New Guinea. *Papua New Guinea Journal of Agriculture, Forestry and Fisheries* 41: 85-90 (This issue)

SANCHEZ, P.A. (1995). Science in agroforestry . *Agroforestry system* 30: 5-55.

SHANNON, D.A. and **VOGEL, W.O.** (1994) The effects of alley cropping and fertilizer application on continuously cropped maize. *Tropical Agriculture* 71: 163-169

TURNBULL, J.W. (1986) *Multipurpose Australian trees and shrubs, lesser-known species for fuelwood and agroforestry.* ACIAR Monograph 1. ACIAR, Canberra

XU, Z.H., SAFFIGNA, P.G., MYERS, R.J.K., and **CHAPMAN, A.L.** (1992) Nitrogen fertilizer in *Leucaena* alley cropping I: Maize response to nitrogen fertilizer and fate of fertilizer-15N. *Fertilizer Research* 33: 219-227

YOUN, A. (1989) *Agroforestry for soil conservation.* CAB International, Wallingford.

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TROBEN, M.M. (1973). Genetic fine structure in Drosophila. *Department of Primary Industry Research Bulletin* No. 102: 196-197.

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