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Final report

project	**Overcoming magnesium deficiency in oil palm crops on volcanic ash soils of Papua New Guinea**
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Contents

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2 Abbreviations

CEC	cation exchange capacity
CSIRO	Commonwealth Scientific and Industrial Research Organisation (Australia)
CTP	CTP Holdings Pte. Ltd., a subsidiary of Cargill Inc.
DM	dry matter
EC	electrical conductivity of 1:5 soil:water extract
ECEC	Effective cation exchange capacity (sum of exchangeable cations)
EFB	Empty fruit bunches (mill byproduct produced following removal of fruit)
EMAG45	Magnesium oxide (QMAG product name, produced by heating magnesium carbonate)
FFB	Fresh fruit bunches (as harvested)
FO1	Magnesium carbonate, as mined (QMAG product name)
JCU	James Cook University
KIE	kieserite (magnesium sulphate)
MBP	Milne Bay Province
MOP	Muriate of potash (mostly KCl)
MP	Morobe Province
M30	Mix of magnesium carbonate and magnesium oxide (QMAG product name, partially calcined $MgCO_3$)
NARI	National Agricultural Research Institute (PNG)
NBPOL	New Britain Palm Oil Ltd.
NIP	New Ireland Province
NUE	nutrient use efficiency
OP	Oro Province
OPIC	Oil Palm Industry Corporation
OPRS	Oil Palm Research Station (NBPOL, Dami)
PNGOPRA	Papua New Guinea Oil Palm Research Association
POME	palm oil mill effluent
QMAG	Queensland Magnesia
RAI	Ramu Agri-Industries
TPB K	Tetraphenyl borate-extractable K
WNBP	West New Britain Province

3 Executive summary

Oil palm is the most important crop in Papua New Guinea in terms of export income, earning K800 million in 2007. It is grown by plantation companies and smallholders. About 45% of the area under oil palm, but only about 32% of the production, comes from smallholders, so there is large potential to increase smallholder productivity. The main agronomic limitation to smallholder productivity is inadequate application of fertilisers.

The aims of this project were to overcome limitations to productivity caused by Mg and K deficiencies. On volcanic ash soils in West New Britain symptoms of Mg deficiency are widespread and leaf Mg concentrations are often low, but Mg fertiliser (kieserite) additions in trials had failed to significantly increase yields. It was proposed that the high Ca content of the soils, combined with high rainfall and high soil permeability, led to rapid leaching loss from the root zone of Mg. This project aimed to a) determine if Mg nutrition was limiting yield, and b) assess alternative strategies for supplying Mg to the palms. In New Ireland, Milne Bay and Morobe Provinces, productivity on alluvial and corraline soils is limited by K deficiency, and economic responses to K fertiliser (muriate of potash) had been established. However, large losses by leaching were suspected. This project aimed to determine the fate of applied K in alluvial soils and determine whether uptake efficiency could be improved.

Field trials were established on the volcanic ash soils to assess the effectiveness of fertilisers with different solubility (Mg oxide, Mg carbonate and Mg sulphate) and placement of Mg and K fertilisers on the surface or in buried ‘hotspots’ with or without barriers to slow leaching loss. Field trials were established on the alluvial soils to determine response to K where it was not yet known, and to assess K placement (broadcast vs concentrated in zones). Leaf nutrient concentrations have responded to treatments in some trials but there have not yet been any consistent yield responses. The trials were established 1-4 years ago and it is known that responses can take several years to develop, so the intention is for them to continue for 10 years.

The fate of Mg and K applied in fertiliser was determined by measurements in the field and laboratory. The volcanic ash soils had high ability to retain Mg (high cation exchange capacity) and there was little or no loss from the root zone by leaching, even when Mg was applied as soluble kieserite. In the alluvial soils, there was little or no loss of K and substantial fixation in non-exchangeable form due to the presence of smectite or vermiculite. The retention of K by the soil leads to low uptake efficiency. Modelling of Mg and K transport closely reflected field results, so modelling can be used to predict the fate of fertilisers in new situations.

Uptake of Mg and K, and their distribution through the canopy were strongly influenced by genotype and also by palm age. Fronds, leaflets and parts of leaflets showing deficiency symptoms (chlorosis) invariably had lower Mg concentrations than plant parts without chlorosis. The research confirmed that frond 17 is still an appropriate frond for diagnosis of Mg and K deficiencies. Maps of nutrient concentrations in smallholder palms indicate clusters of K deficiency. This information can be used to target extension.

Impacts of the research are already apparent, with plantation companies reassessing the type and manner of fertiliser applications. For smallholders it is clear that overcoming N deficiency should be the primary aim in most areas. As results from the field trials become clear, the project is expected to have a large economic impact through changed fertiliser management practices. There has been a major capacity impact due to training of Oil Palm Industry Corporation (OPIC) extension officers, PNG Oil Palm Research Association (PNGOPRA) research staff, smallholder growers and plantation managers in nutrition-related issues.

4 Background

Palm oil industry in PNG, and oil palm nutrition issues

Oil palm (*Elaeis guineensis* Jacq.) is the most important crop in Papua New Guinea (PNG) in terms of export income (K800m in 2007), directly supporting over 18,000 smallholders and driving the cash economies of the four provinces in which it is grown. PNG has about 130,000 ha of oil palm (Table 1). About 45% of the area, but only about 32% of the country's production, comes from smallholder blocks, so there is large potential to increase smallholder productivity. The main agronomic limitation to smallholder productivity is inadequate applications of fertiliser.

Table 1. Oil palm area and production for PNG in 2006.

Province[1]	**Company**[1]	**Plantation**[1]	**Smallholder**	**Total**
Area estimates (ha)				
West New Britain (WNBP)	NBPOL	34,774	23,997	58,771
West New Britain (WNBP)	Hargy Oil Palm	6,456	14,329	20,784
Oro (OP)	Higaturu Oil Palm (CTP[2])	8,892	14,285	23,177
Milne Bay (MBP)	Milne Bay Estates (CTP[2])	11,575	1,499	13,074
New Ireland (NIP)	Poliamba Estates (CTP[2])	5,689	1,902	7,591
TOTAL		67,386	56,012	123,398
FFB production (tonnes)				
West New Britain (WNBP)	NBPOL	692,807	338,951	1,031,758
West New Britain (WNBP)	Hargy Oil Palm	156,276	138,449	294,725
Oro (OP)	Higaturu Oil Palm (CTP[2])	147,324	150,956	298,280
Milne Bay (MBP)	Milne Bay Estates (CTP[2])	226,284	10,282	236,566
New Ireland (NIP)	Poliamba Estates (CTP[2])	133,027	17,481	150,508
TOTAL		1,355,719	656,119	2,011,837

[1] Companies own the mills and 'Plantation'. Ramu (Morobe Province) was not yet producing in 2006.

[2] CTP Holdings, formerly PacRim, and before that, CDC.

A significant proportion of the oil palm production is to be found in West New Britain Province (about 65% of total area and 68% of smallholder area), and symptoms of Mg deficiency have been noted there since the first years of production (Mendham, 1971). Soils of the province on which oil palm is grown are coarse textured volcanic ash of recent origin and receive an annual rainfall that exceeds 3000 mm. Much of the oil palm growing in the West New Britain exhibits a characteristic yellowing or chlorosis of the lower canopy (Figure 1). This chlorosis has the typical characteristics of Mg deficiency symptoms. Magnesium deficiency symptoms are also seen in other parts of the country, and are marked in the Ilimo-Papaki and Mamba areas of Oro Province.

In the late 1980's, nitrogenous fertiliser inputs were introduced for both smallholder and plantation crops in order to maintain acceptable oil palm yields. This change in management practice has had an enormous impact on increased production for all grower types. However as the deficient nitrogen status of palms has been ameliorated, the severity of symptoms characteristic of Mg deficiency have increased.

Commencing in the 1980's, trials with Mg fertiliser (kieserite) were established in all oil palm growing provinces except Milne Bay. However, in most areas kieserite additions generally failed to significantly increase yields. In spite of the general lack of response to soluble Mg fertilisers, Mg deficiency is still believed to be the cause of chlorosis symptoms and thus responsible for lost production. The suggestion that Mg is a limiting nutrient derived from (a) the generally low level of Mg found in the diagnostic frond (frond 17), (b) the characteristic symptoms, and (c) the particular nature of the soils, combined with high rainfall.

It has not been possible to quantify the lost production potential through standard agronomic experiments owing to lack of yield response to Mg applications. However, a crude measure of lost production is obtained by comparing fruit bunch yields achieved in New Britain Palm Oil (NBPOL) plantations, 26 t/ha, with what should be expected for well managed palms on good soils, viz. 32 t/ha. Potential yield in West New Britain was initially shown to be 35 t/ha before nutrient deficiencies started to become apparent (Mendham, 1971). Crude palm oil yields are approximately 20-23% of fruit bunch yields. Increasing fruit production from 26 to 32 t/ha over the area in which the problem occurs (60% of the PNG industry) would increase annual crude palm oil production in PNG from 320,000 t to 371,600 t. The price of palm oil has fluctuated in recent years (around USD300-1200 during the period of this project, on a general upward trend), but assuming a figure of AUD 1000/t, the increased revenue would be AUD 51m per annum. This figure does not include palm kernel, from which oil may be extracted (about 5% of fruit bunch yields) or which may be sold without processing.

Potassium deficiency is also widespread within the industry, being particularly marked in Milne Bay Province and New Ireland Province. Typical symptoms are shown in Figure 2. Marked agronomic and economic responses to K fertiliser have been obtained in PNGOPRA trials in those provinces, unlike the Mg fertiliser trials in West New Britain. However, the high costs of K fertiliser applications leads to the question as to whether nutrient use efficiency can be improved.

Link between Mg and K deficiencies and soil properties

Magnesium deficiency and deficiency symptoms have been reported in oil palm in a number of other regions of the world and generally yields respond to Mg application (Turner, 1981). However, trials in West New Britain have shown that even high levels of prolonged Mg fertiliser (kieserite) input have limited or no impact on yields. Because the symptom is widespread across West New Britain and also occurs in some parts of Oro Province, PNGOPRA has targeted the correction of this problem as a major strategic goal.

Figure 1: Symptoms of Mg deficiency, occurring in many parts of West New Britain Province.

Figure 2**: 'Orange-spotting' symptoms, associated with K deficiency.**

As PNG does not have in-country facilities or expertise to address the necessary research problem, in 1999 PNGOPRA approached Dr. Gavin Gillman for assistance. The oil palm producers of PNG then financed, through PNGOPRA, a pilot study to determine the basic cause of the problem (Gillman and Gillman, 2001).

In the pilot study, analyses of soils (30 x 1m profiles = 150 samples) from West New Britain Province indicated that the soils' ability to retain Ca, Mg and K (cation exchange capacity, CEC) was reasonably high, but dependent on soil pH and solution ionic strength ('variable charge' soils). More importantly, these 'variable charge soils' have a serious cation imbalance that may hamper adequate Mg nutrition. The problem is best summed up in Figure 3, showing trends in CEC and exchangeable cations in a soil profile. The graph is typical of the 30 West New Britain profiles examined. The fluctuations with depth are due to the layered nature of the soils. Thickness and number of layers has been determined by ash falls and alluvial redistribution over the last few thousand years. Most profiles had exchangeable Ca greater than CEC in some or all horizons. Exchangeable Ca contents were much higher than exchangeable Mg contents in all profiles (Gillman and Gillman, 2001).

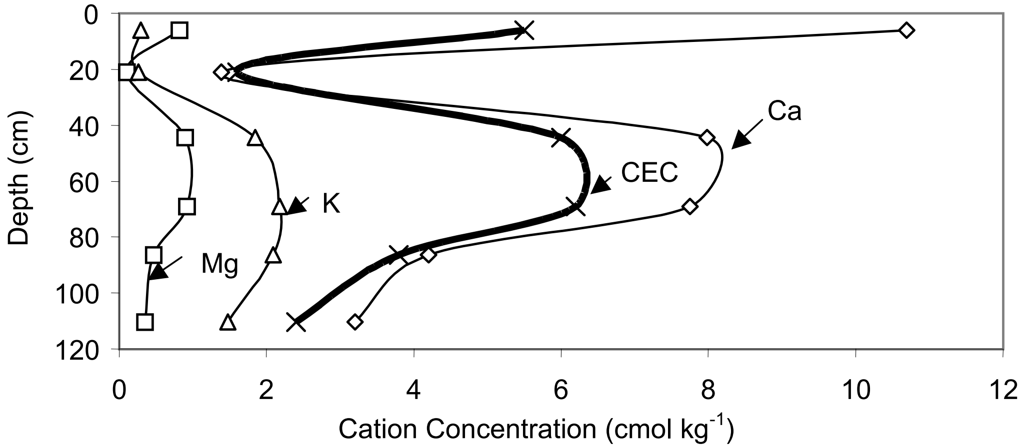

Figure 3**. Exchangeable cations and CEC in a typical soil profile from West New Britain (Kumbango).**

Clearly, the cation exchange capacity of West New Britain soils is overwhelmed by Ca, and there is a severe Ca:Mg imbalance. It was hypothesized that Ca would restrict the entry of applied Mg or K ions to cation exchange sites, meaning that Mg or K applied in soluble form would be rapidly leached through the profile. The high concentration of extractable Ca, greater than the CEC, suggested a source, as yet unidentified, which is capable of continually supplying Ca. This could mean that other cations, such as Mg and K, even if added in large quantities, could be displaced from the exchange complex by newly available Ca and then rapidly leached out of the system. This project was developed based on that hypothesis.

In the 4 profiles from Oro Province that were examined, the characteristics described above were not evident; exchangeable Ca contents were lower than CEC and not much greater than exchangeable Mg contents. However, the profiles from the Kokoda area of Oro Province had very low exchangeable cation contents and CECs. In this case, it was suggested that the high rainfall and low CEC means that highly soluble fertilisers such as kieserite and KCl would have a very short residence time in the root zone – thereby resulting in Mg and K deficiency.

Based on PNGOPRA trials work with soluble Mg fertiliser (kieserite), economically viable Mg fertiliser recommendations cannot be made when the cost/benefit ratio is considered. This leaves the smallholder growers, in particular, with a serious problem. They must apply nitrogenous fertiliser to maintain acceptable yield levels, but when they do this symptoms of Mg deficiency appear, and the severity increases with time and nitrogen usage. This problem is not confined to oil palm, but affects most cash and food crops growing on the affected soils. ACIAR discussions with the National Agricultural Research Institute in PNG (NARI) have revealed that similar problems seem to occur on most of the coastal lowland volcanic soils on the north coast of PNG and the Bismarck Archipelago.

The K deficiencies in Milne Bay, Morobe (Ramu) and New Ireland Provinces may also be related to soil properties, but no detailed soil analyses had been done, so that question was examined in the project.

The approach taken in this project

This project originally set out to determine whether or not Mg nutrition was limiting production in West New Britain and parts of Oro Province, and if so, how to solve the deficiency. Because the length of time for oil palm yield to respond to fertiliser additions is long in the context of a 3-5 year research project, a ‘two-pronged’ approach was proposed. One approach was a ‘best-bet’ approach based on the information at hand to design a fertiliser strategy for each particular situation. The ‘best bet’ approach focussed on the use of fertiliser placement strategies along with slow release technologies to maintain a Mg (and possibly K) dominance in at least part of the root zone. The other approach was a strategic one aimed at definitively identifying the nature and extent of deficiency(ies) and the underlying causes and extent in order to design a strategy, including improved tissue diagnostics, to manage the deficiency across problem soils in PNG, and possibly other oil palm regions.

The project started in September 2002 and finished in August 2008. Following the mid-term review in December 2004, the project was expanded to include K nutrition issues in Milne Bay, Morobe (Ramu) and New Ireland Provinces. As part of that expansion, James Cook University was added to the original project team of PNGOPRA and CSIRO. Due to staff changes, the project leaders changed several times during the life of the project. The Australian project leaders were Mike Webb (CSIRO), then Sue Berthelsen (CSIRO) and then Paul Nelson (JCU). The PNG project leaders were Paul Nelson, then Mike Webb and finally Harm van Rees (all PNGOPRA).

5 Objectives

The initial overall aim of the project was to increase yields of oil palm by overcoming the deficiency causing symptoms characteristic of Mg deficiency on volcanic ash soils in lowland PNG. Following the mid-term review, another aim was added: to increase yields of oil palm by overcoming K deficiency in Milne Bay, Morobe and New Ireland Provinces. The overall aims were to be achieved by providing a stable source of nutrient cations in balanced quantities. The technology required and the portability of that technology, was to be enhanced by an understanding of soil properties across a range of sites, the ameliorant properties, and palm nutrition. From this, predictions of the likely fate of applied Mg and K could be developed to assist in determining the most appropriate way of adding Mg and K (Figure 4).

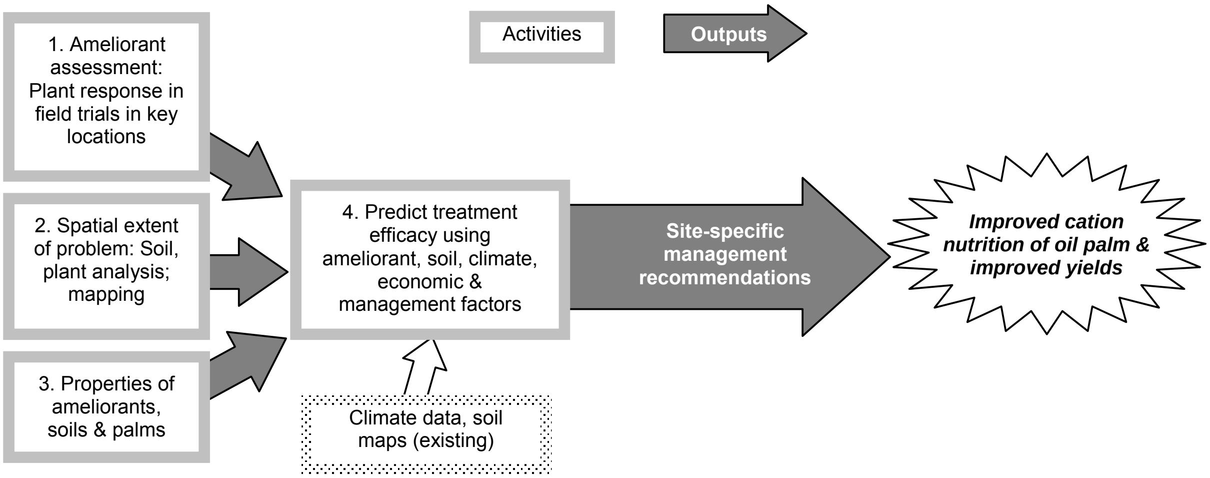

Figure 4: Summary of relationship between proposed activities and outputs in the project

Specific objectives were:

1. Assessment of slow-release Mg-containing amendments and application methods in field trials (Mg and K amendments) on a range of problem soils.
   Output: Yield and economic response of oil palm to amendments and quantification of supply, uptake, losses, and use efficiency of applied cations.
2. Assessment of spatial extent of problem, using soil and plant analysis and soil map interpretation.
   Output: Understanding of the linkage between soil properties and cation nutrient deficiency in oil palm, embodied in soil maps and deficiency assessment ratings.
3. Measure properties of soils, amendments and palms that will enable extrapolation of trial results by enhancing understanding of processes.
   Output: Chemical and hydraulic properties of soils necessary for extrapolation of trial results to all parts of the region dominated by volcanic ash soils. Independent confirmation of nutrient deficiencies through glasshouse trial. Alternative diagnostic criteria.
4. Predict treatment efficacy using ameliorant, soil, climate/environment, cost, management factors
   Output: Recommendations for management of cation deficiencies /imbalances of oil palm on volcanic ash soils.

6 Methodology

6.1 Project locations

The project was carried out mostly in West New Britain Province, where Mg deficiency symptoms are most common. However, some work was carried out in Oro Province, and following the expansion of the project to cover K deficiency issues, work was carried out in Milne Bay, New Ireland and Morobe Provinces. The main locations mentioned in this report are shown in Figure 5.

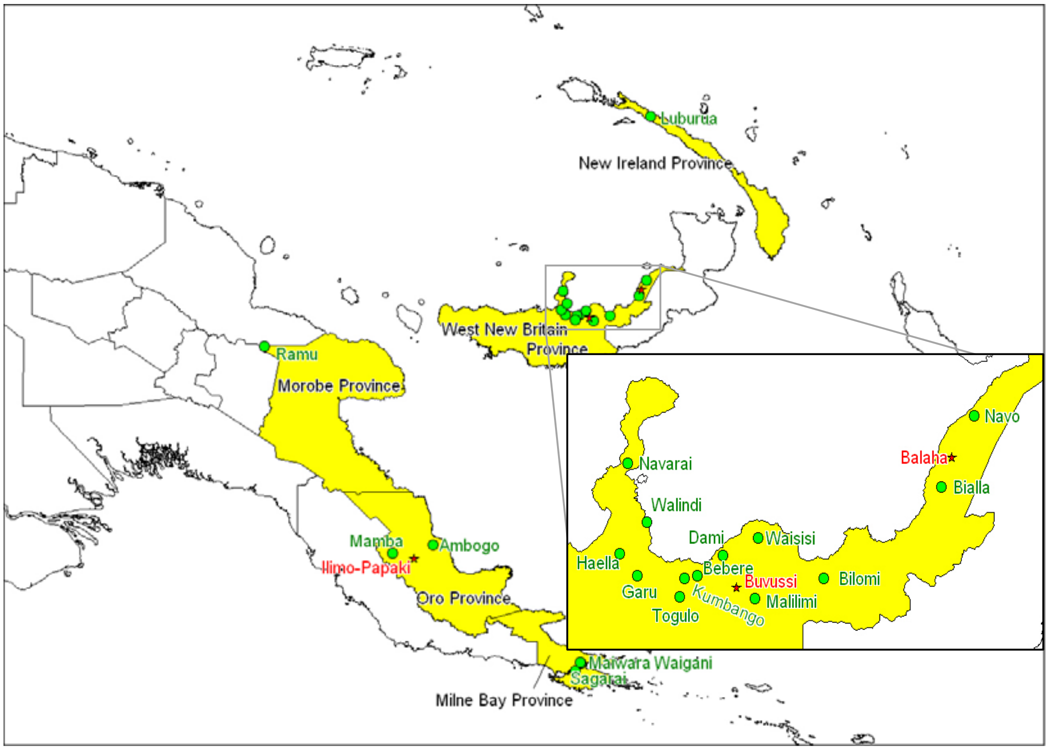

Figure 5: Map of Papua New Guinea, showing research sites mentioned in the text. Plantation names are shown in green, smallholder areas in red and provinces in black.

6.2 Soil sampling and analysis

Extensive soil sampling and analysis was carried out. Chemical analyses were carried out in CSIRO Davies laboratory, mineralogical analyses were carried out in CSIRO Adelaide, and physical analyses were carried out in the field and in CSIRO Davies laboratory. The soil analysis data sets are summarized in Table 2, and locations of all sites are given in Appendix 1.

Table 2. Summary of soil and leaf analyses. See **Appendix 1** for locations.

Sample set	Year sampled	Province (no. of sites)	Soil analyses	leaf analyses
Gillman[1]	2000	WNBP (22), OP (5)	yes	no
Field trials	2002-2008	WNBP (5), MBP(2), MP(1)	yes	yes
Soil pits	2006	WNBP (5), MP (3), MBP (4), NIP (2)	yes	no
Oro smallholders	2001	OP (31)	yes	yes
Hoskins smallholders	2001	WNBP (30)	yes	yes
Bialla smallholders	2004	WNBP (48) No soil samples	no	yes

[1] Sampled in previous project (Gillman and Gillman, 2001), but further analysed in this project

CEC was determined by saturation with Ca and subsequent displacement (with 1M NH_4NO_3) and measurement of Ca^{2+} and Al^{3+} (Gillman and Sumpter, 1986). Contents of exchangeable Ca^{2+}, Mg^{2+}, K^+ and Na^+ were determined using displacement with 0.1 *M* $BaCl_2$-NH_4Cl (Gillman and Sumpter, 1986). The concentration of ions in soil solution was measured after wetting the soils to saturation and extracting the solution in a centrifuge. Phosphate retention and phosphate sorption index were was determined according to Rayment and Higginson (1992).

Various forms of soil Mg (in Trial 151; 0-10 cm) were determined using a sequential extraction procedures based on that of Uzo Mokwunye and Melsted, (1972). The extractants used were 0.1*M* $BaCl_2/NH_4Cl$ (exchangeable Mg, carried out 6x to ensure complete recovery); 1*M* NH_4Cl (more strongly held exchangeable Mg), H_2O_2 oxidation followed by 0.1*M* $BaCl_2/NH_4Cl$ (organic–complexed Mg) , boiling 1*N* HNO_3 (acid soluble Mg), and finally digestion with a tri-acid mixture of HNO_3, H_3PO_4 and $HClO_4$ (mineral Mg). Soil from the control plots (no added fertiliser) was analysed by XRF to determine total Mg of the soil.

Mineralogy was determined from X-ray fluorescence (XRF) of fused samples and X-ray diffraction (XRD) measurements of powder samples. The content of allophane was determined using oxalate-extractible Al and Si and pyrophosphate-extractible Al (Parfitt, 1990). The content of poorly crystalline Fe oxides was determined using oxalate-extractible Fe (Childs, 1992). The sources of tephra for the soils were differentiated using two indices. One source index (SIa) was the 'differentiation index' (DI) of Thornton and Tuttle (1960). The other source index (SIb) was the elemental mass ratio of Zr to Ti. Zr and Ti are two of the most stable soil elements and compared with most other elements are least affected by weathering and translocation processes occurring within the soil (Fitzpatrick and Chittleborough, 2002). Two indices for the degree of weathering of soils were calculated. One (WIa) was calculated by adding the percentages of the secondary minerals halloysite, smectite (mean of ranges given in Table 13) and allophane. The other weathering index (WIb) was the molar ratio of Al/Ca+Mg+K+Na.

The ability of the soils to retain added cations was determined by establishing adsorption isotherms for K and Mg. KCl or $MgSO_4$ was added to the soils in a range of concentrations (1:10 soil:solution ratio) and after equilibration (16 hours shaking) the concentrations of exchangeable cations and solution cations were measured. The data were fitted to the Freundlich-Langmuir equation as described in section 6.3.

The relative strength with which cations were retained by the soils, or cation exchange selectivity, was measured by establishing adsorption isotherms over a range of cation ratios, at constant ionic strength. As Ca was the dominant exchangeable cation in all soils, the adsorption isotherms were established using Ca/K or Ca/Mg pairs. In most cases the soils were first saturated with Ca. The isotherms were measured at ionic strengths of I = 1 or 4 mM and using chloride or nitrate as the anion.

Water retention curves and bulk density were determined on undisturbed 70 x 50 mm cores. Water retention curves were determined using pressure plates.

Saturated infiltration rates, or 'infiltrability', were measured in the field, at the surface, and within major horizons. Measurements were made using falling head single ring infiltrometers, either 25 or 40 cm in diameter. The value used was the rate of infiltration when it had reached a steady state

6.3 Modelling Cation Movement through Soil

The water and solute modelling software, HYDRUS-1D (Simunek et al., 1998) was used to predict the movement of Mg and K through different soils. The data required to run the model are: rainfall, and soil saturated infiltration rate, water retention curves, bulk density, and the adsorption isotherms for Mg and K. Rainfall information was either collected specifically at the site of the trials using a large number of collectors, was obtained from automated weather stations nearby.

Water retention data were fitted to the van Genuchten equation:

$$\Theta = \Theta_r + \frac{\Theta_s - \Theta_r}{\left[1 + |\alpha h|^n\right]^m}$$

where:

θ is the volumetric water content
θ_r is the residual water content
θ_s is the saturated water content
h is the pressure head
α, m, and n are empirical parameters to be estimated

Microsoft Excel's Solver tool was used to fit the data and estimate the parameters.

Cation adsorption isotherm data were fitted to Freundlich-Langmuir equation:

$$AdsIon = \frac{(CEC * \eta * SolIon^{\beta})}{(1 + \eta * SolIon^{\beta})}$$

AdsIon is the concentration of ion on the exchange site
SolIon is the concentration of the ion in solution
CEC is the cation exchange capacity
η and β are empirical parameters to be estimated
in HYDRUS-1D the parameter Kd is equivalent to $CEC*\eta$

Again, Microsoft Excel's Solver tool was used to fit the data and estimate the parameters.

Data has been collected for a number of sites making it possible Mg and K movement under differing rainfall patterns (Table 3).

Table 3: Locations that have the required information to run HYDRUS simulations of Mg and K movement.

Province	Site	Trials	Infiltration rates	Water retention	Cations CEC pH	Adsorption isotherms	Soil Description	Particle size
Morobe	Ramu-1	RM1	√	√	√		√	√
	Ramu-2	RM1	√	√	√	K	√	√
	Ramu-3	RM2	√	√	√	K	√	√
New Ireland	Poliamba-1	T251	√	√	√	Mg, K	√	√
	Poliamba-2	T251	√	√	√		√	√
West New Britain	Bialla	T214	√	√		Mg, K	√	√
	Waisisi-2005	T144	√	√	√		√	√
	Waisisi-2006	T144	√	√	√	Mg	√	√
	Dami	T151	√	√	√	Mg	√	√
	Kumbango	T146	√	√	√	Mg	√	√
	Walindi	T145			√	Mg		
	Navo	T151	√	√	√	Mg, K	√	
Milne Bay	Waigani	T502b	√	√	√	K	√	√
	Sagarai	T504	√	√	√	K	√	√
	Maiwara-1	T516	√	√	√	K	√	√
	Maiwara-2	T516	√	√	√		√	√

6.4 Trial work

Details of trial layout, treatments, location, and soil are provided in the project annual reports and in PNGOPRA annual reports. A brief description for each trial is provided in the achievements section (7.1). Trials were analysed by ANOVA. In all cases effects with $p<0.05$ are reported as ‘not significant’.

7 Achievements against activities and outputs/milestones

Objective 1: Assessment of slow-release ameliorants and application methods in field trials on a range of problem soils

No.	Activity	Outputs/ milestones	Completion date	Comments
1.a	Field trials, West New Britain Province (PC, A)	Treatments and first sampling	T144 2003 T145, 2004 T146, 2004	More field trials were established than originally planned in the project document
		Second sampling	T145, 2007 T146, 2008	T144 to be done by OPRA
1.b	Field trials, Oro Province (PC, A)	Treatments and first sampling	T333,2004	
		Second sampling		Trial abandoned because of poor palm performance
1.c	Organic matter hot spots (PC, A)	Samples collected and analysed	2005	In T129
1.d	Follow up field trial, West New Britain Province (PC)	Treatments and first sampling	T151, 2007	
		Second sampling	T151, 2008	
1.e[1]	Field trial, Milne Bay Province (PC)	Site selected and soil sampled for initial characterisation	T516/517, 2006 T502b, 2006	To be continued by OPRA OPRA trial sampled in this project
1.f[1]	Field trial in Morobe Province (PC)	Sampling strategy designed	RM03-1, 2006	Soils collected and analysed for chemical and hydraulic properties

PC = partner country, A = Australia

1 Added following mid-term review in December 2004

Objective 2: Assessment of spatial extent of problem, using soil and plant analysis and soil map interpretation

no.	activity	outputs/ milestones	completion date	comments
2.a	Cation status of soils (PC, A)	Samples collected and analysed	2004	
2.b	Cation uptake (PC, A)	Sample collection and analysis	2004, 2005, 2006	Part of routine sampling by OPRA
2.c	Maps of leaf Mg contents (PC)	Maps produced	2005	
2.d	Maps of predicted nutrient deficiencies (PC)	Maps of nutrient deficiencies produced	2006	This also contributed to the AIGF (AusAID) project “Site specific fertiliser recommendations to increase income of smallholder oil palm producers in West New Britain Province”

PC = partner country, A = Australia

Objective 3: Measure properties of soils, amendments and palms that will enable extrapolation of trial results by enhancing understanding of processes

no.	activity	outputs/ milestones	completion date	comments
3.a	Soil Properties (PC, A)	Soils sampled. Selectivity, mineralogy, and hydraulic properties determined	2004 2007	Many soils have been sampled and analysed during the life of the project
3.b	Ameliorant properties (A)	Solubility and breakdown of ameliorants determined	2004 (lab) 2008 (field)	
3.c	Palm physiology (PC, A)	Partitioning of cations determined	2004, 2006	
3.d	Independent determination of nutrient status (A)	Glasshouse trials	2004	
3.e	Alternative diagnostic criteria (PC, A)	Alternative leaves sampled and analysed	2005	
3.f	Effect of other nutrients (PC)	Pot trials		Mid-term review recommended that this activity be cancelled
3.g[1]	Speciation of cations and link with HYDRUS (A)	Ca/Mg/K exchange chemistry	2007	
3.h[1]	Root distribution and proliferation	Field studies on root distribution Glasshouse trial on root proliferation	2006 2006	
3.i[1]	Cation dynamics and competition	Additional analysis of sample already collected Glasshouse trials	2007 2007	
3.j[1]	Fates of solutes	Experiments on Mg and K movement	2007	

PC = partner country, A = Australia

[1] Added following mid-term review in December 2004

Objective 4: Predict treatment efficacy using ameliorant, soil, climate/environment, cost, management factors

no.	activity	outputs/ milestones	completion date	comments
4.a	Modelling Mg and K using results from other activities (PC, A)	Site-specification management recommendations for Mg and K		

PC = partner country, A = Australia

Objective 5: Training staff

no.	activity	outputs/ milestones	completion date	comments
5.1	Courses, workshops, publications	Many training activities were undertaken during the life of this project.	2002-2007	See Impacts – Capacity

PC = partner country, A = Australia

7.1 Details of achievements

7.1.1 Objective 1: Assessment of slow-release ameliorants and application methods in field trials on a range of problem soils

A major component of this project was the establishment of five field trials. These field trials required a large effort to establish and maintain. They mostly consist of plots (~2,700 m^2) having 6x6 treated palms, of which the inner 4x4 are monitored. Standard monitoring includes harvesting every 7-14 days, leaf sampling and analysis and vegetative measurements. The harvest recordings are made on an individual palm basis. In addition, several of the trials were intensively sampled and analysed (soil and leaf samples) in this project. Yield responses to treatments can only be expected after 5 or more years, and the continued maintenance of some of the trials and interpretation of results has been taken on by PNGOPRA.

Activity 1.a: Field trials, West New Britain Province

Three long-term field trials were established in West New Britain Province (original proposal only specified two trials).

Trial 144 (Waisisi) was established on a new area which did not have a history of Mg fertiliser. As it was also suspected of being low in K, a factorial (K x Mg) trial was established to demonstrate a response to both Mg and K. This trial has been harvested and sampled since 2003. It consists of 16 plots and 256 monitored palms.

Trial 145 (Walindi) was established in an existing plantation in an area suspected of being Mg deficient (symptoms apparent on fronds). This trial was designed to compare a number of sources of Mg ($MgSO_4$ [Kieserite]; $MgCO_3$ [FO1]; MgO ([MAG 45]; MCO_3/MgO mix [EMAG M30]) at a standard rate of Mg and twice the standard rate. This trial was established in 2004 and has been harvested and leaf-sampled since. There have been two soil samplings; the latest being in 2007 to determine the fate of applied Mg. The trial consists of 48 plots and 768 monitored palms.

Trial 146 (Kumbango) was established in a plantation in an area suspected of being Mg deficient (symptoms apparent on fronds). This trials was designed to compare a number of Mg sources (Kieserite, FO1, EMAG 45) by a number of placement methods (on the surface, in a trench, in trench protected by plastic, in an upturned coconut shell). This trial was established in 2004 and has been harvested and leaf-sampled since. There have been two soil samplings; the latest being in 2008 to determine the fate and movement of applied Mg. The trial consists of 56 plots and 896 monitored palms.

Although not strictly part of this project, Trial 148 (Kumbango), established by PNGOPRA in 2003, is relevant to this project. It aims to overcome the problem of small plots (potential movement of nutrients between plots) and progeny effects by overlaying Mg treatments (different rates of kieserite) on three OPRS breeding trials. The three breeding trials (282, 283 and 284) were planted in 2001. Each of them is a replicate of the fertiliser trial. The whole fertiliser trial consists of 252 plots (3 breeding trials with 84 in each) and 3024 monitored palms.

Activity 1.b: Field trial, Oro Province

Trial 333 (Mamba) was established in an area where the soils have very low CEC and thus suspected of being deficient in the supply of Mg and K. The treatment design is quite complicated but consists of a Mg source set, a K source and placement set, and a Mg x K factorial. Pre-treatment soil sampling was carried out in 2004, as well as harvesting and leaf-sampling from 2004 to 2007. However, this site was abandoned because of poor palm performance and maintenance; resulting in yield potential not being achieved.

Activity 1.c: Organic matter hot spots

Soil was sampled under different zones receiving either additional organic matter or fertilisers to determine the effects of these treatments on soil fertility and thus likelihood of supply Mg and K.

Activity 1.d: Follow up field trial, West New Britain Province

Trial 151 at Dami and at Navo were set up to investigate the movement of Mg and other ions through the profile.

Activity 1.e: Field trial, Milne Bay Province

A field trial (T516/517) was established at Maiwara in a young planting to determine the effect of N and K rates and K placement on yield. Most of the plantings in Milne Bay Estates show signs of K deficiency if not supplemented with K fertiliser. However, we have found in the project that K accumulates in the top 70 cm of the soil. Trial 516 examines NxK interactions and Trial 517 studies the effect of placing K in different zones. The trial was established in 2006 and will be continued by OPRA. Trial 517 consists of 16 plots and 256 monitored palms

Activity 1.f: Field trial, Morobe Province

This trial (RM 03-1) was established by PNGOPRA in 2003. It is a factorial trial (N x K x P x S). It was included as part of this project during the expansion phase in order to investigate K nutrition in this young planting. Soil samples were taken to characterise the chemical properties and pits were dug to characterise the physical and hydraulic properties of various soil layers.

7.1.2 Objective 2: Assessment of spatial extent of problem, using soil and plant analysis and soil map interpretation

Activity 2.a: Cation status of soils

Thirty soil and leaf samples were collected from smallholder blocks in the Hoskins area and 31 samples in Oro Province (2001). These were analysed for cation status. Samples collected by Gillman and Gillman (2001) were further analysed and their positions related to their vicinity of the volcanoes which contributed ash to the soil profile.

Activity 2.b: Cation uptake

Soil and leaf samples were collected as routine activity of PNG OPRA over a number of years and at a number of sites – depending on the number of active trials.

Activity 2.c: Maps of leaf Mg contents

Because Mg and K containing fertilisers are not generally applied in smallholder blocks, analysis of leaf samples from these blocks can reveal the Mg and K status of the soil and geospatial patterns.

Activity 2.d: Maps of predicted nutrient deficiencies

In association with another project (AIGF) nutrient requirements of smallholder blocks were determined from nutrient use in nearby plantations on the same soil type. These maps have been expressed in terms of how much fertiliser should be applied to achieve yields similar to the plantations. These maps can also be interpreted as the likelihood of a particular nutrient deficiency.

7.1.3 Objective 3: Measure properties of soils, amendments and palms that will enable extrapolation of trial results by enhancing understanding of processes

Activity 3.a: Soil properties

Soil chemical (pH, EC, exchangeable cations, CEC, adsorption isotherms), physical (bulk density, particle size, mineralogy), and hydraulic (water retention, infiltration rate) properties have been determined on a wide range of soils (Ramu x3, Kumbango, Navo, Poliamba x2, Waigani, Sagarai, Maiwara x2, Waisisi x2, Dami). These properties have been used to measure as well as model Mg and K movement through the soil.

Activity 3.b: Ameliorant properties

Properties of Mg products (Table 4) which might be suitable candidates as an alternative to the soluble kieserite were determined in a number of experiments. For K, there are no real alternatives to muriate of potash (KCl), apart from EFB, which contains large amounts of K, and has a K:Mg ratio similar to that required by palms.

Table 4: Names and some properties of Mg products

Chemical name	Chemical formula	Mineral name	Other names	Description
Magnesium sulphate	$MgSO_4 \bullet H_20$	Kieserite		By-product
Magnesium carbonate	$MgCO_3$	Magnesite	FO1	Mined
Magnesium oxide	MgO		EMAG 45 & EMAG 500	Fully calcined
	$MgCO_3/MgO$		EMAG M30	Partially calcined
Magnesium silicate		Olivine		

Laboratory experiments were carried out to determine solubility and glasshouse experiments were carried out to determine their vulnerability to leaching and their ability to supply Mg to palms. Different products were also trialled in the field (see 7.1.1 above).

Activity 3.c: Palm physiology

The distribution of Mg throughout fronds and rachis has been determined in a number of trials and smallholder blocks. The relationship between Mg deficiency symptoms and leaf Mg levels has also been explored and in some cases related to the genetics of palm parents (so-called progeny effect).

Activity 3.d: Independent determination of nutrient status

Two omission trials in pots were set up in both Townsville and Dami as an alternative way of establishing the soil's ability to provide Mg. Both trials in Townsville showed a moderate growth depression in the –Mg treatment compare to the control which had all nutrients supplied in adequate amounts.

Activity 3.e: Alternative diagnostic criteria

Leaflets from frond 17 are the standard for leaf analysis. This leaf was chosen for it ability to discriminate between nitrogen deficiency and sufficiency; not for its suitability for Mg. This project also looked at other leaves for their diagnostic suitability. However, we found no other tissues better than frond 17, and thus would not recommend a change from the standard.

Activity 3.f: Effect of other nutrients on Mg uptake

This activity was cancelled at the mid-term review.

Activity 3.g: Speciation of cations and link with HYDRUS

Speciation modelling studies were carried out in order to understand the nature of Mg under various pH conditions. These were done because soil acidification appears to be occurring at a high rate and may affect the exchange of Mg on the soil surface. In studies with nitrogen fertilisers, it was found that ammonium chloride caused Mg to move further down the profile than when no ammonium chloride was used.

Activity 3.h: Root distribution and proliferation

In collaboration with a project on nitrogen nutrition, root activity distribution was inferred from changes in soil water content and root mass distribution was measured. Most of the roots are found within the top 60cm of the soil.

Activity 3.i: Cation competition

The effect of competing cations (Mg and K) in solution on the uptake of those cations was determined by growing oil palm in solution culture and measuring leaf nutrient levels.

Activity 3.j: Fate of solutes

Two field trials were established to follow the movement of Mg (T151, Dami) and Mg, K and N (T151, Navo) through the profile after careful application of fertilisers to the soil surface. The Dami trial was sampled after 7 weeks, and again after 1 year. The Navo trial was sampled after 10 weeks ((over 1000mm of rain fell during this period).

7.1.4 Objective 4: Predict treatment efficacy using ameliorant, soil, climate/environment, cost, management factors

Activity 4.a: Modelling Mg and K using results from other activities

A number of scenarios have been produced using the various data set collected.

7.1.5 Objective 5: Training staff

A number of courses and training sessions were conducted during the project, either provided by project staff, or given to project staff. This included 8 workshops held for farmer groups/OPIC/plantation staff on aspects of soil science and plant nutrition; workshops and data analysis; industrial training for students from University of Technology and University of Vudal; and a John Allwright Fellowship. These activities are listed below in the Capacity Building section.

Training activities

1. June 2003: Mr Murom Banabas, Dr Paul Nelson, Mr James Kraip, and Dr Mike Webb received training in using HYDRUS-2D; a water and solute modelling software package.
2. Dec 2004: OPIC and NBPOL staff trained in aspects of soil science and plant nutrition.

3. April 2005: James Kraip (OPRA) attended a NARI funded Scientific Writing workshop
4. May 2005: Rachel Pipai and James Kraip attended ACIAR-funded Research Management Workshop in Lae from 18/5/05 to 22/5/05.
5. May 2005: OPIC and Poliamba staff trained in aspects of soil science and plant nutrition.
6. May 2005: Paul Nelson (JCU) attended a Project Management training Course funded by Dept of Nat Resources and Mines.
7. June 2005: Sue Berthelsen attended CSIRO funded training workshops in ‘Workflow’ and ‘Fast Track’ for project management and CSIRO Foundation Skills Training course.
8. June 2005: Steven Nake, James Kraip, Rachel Pipai attended course on “Experimental Design and Sampling” in Lae from the 13th to the 22nd of June
9. July 2005: OPIC and MBE staff trained in aspects of soil science and plant nutrition.
10. July 2005: Rachel Pipai, Steven Nake, Winston Eremu, Ross Safitoa, Wawada Kanama, Dean Woruba and Mike Webb (OPRA) attended a AusAID funded workshop on Statistical Analysis of agricultural trials.
11. July 2005: Paul Nelson (JCU) undertook training in the Riparian Nitrogen Model given by CRC Catchment Hydrology.
12. August 2005: James Kraip (OPRA) attended an Access database training course with funding from OPRA.
13. August 2005: Mike Webb (OPRA) attended a GIS training course funded by Conservation International.
14. Sept 2005: Felix Gitae (Vudal University) visited Alotau in September 2005 and was involved in project meetings and field activities.
15. October 2005: Felix Gitae (Vudal University) and Dr Muhamed Muneer (Lecturer at Unitech) attended the PNGOPRA Scientific Advisory Committee meeting in Port Moresby. Felix Gitae has partially attributed his involvement with this project to his decision to commence PhD studies at Lincoln University in 2006.
16. Nov 2005: OPIC and NBPOL staff trained in aspects of soil science and plant nutrition.
17. Nov 2005: Rachel Pipai attended a digital camera training course.
18. May - October 2005: William Sirabis - student from Unitech spent 6 months with OPRA as part of his formal industrial training and returned for work again from Dec 2005 to February 2006. He was involved with the N loss project, roots distribution studies and was also exposed to other general Agronomy field work such as: trial design, layout and management, data collection and analysis, yield and vegetative measurements, leaf and soil sampling techniques, soil profile description, soil bulk density studies, processing of samples and routine trial maintenance work.
19. Oct 2005 - Feb 2006: Merolyn Koia - student from University of Vudal also spent about 5 months with OPRA as part of her industrial work experience. She was attached with the Agronomy Field staff and was exposed to similar field activities as William Sirabis.
20. Apr 2006: OPIC and Higaturu staff trained in aspects of soil science and plant nutrition.
21. May 2006: Wawada Kanama attended a computer course
22. Nov 2006: NBPOL staff training in oil palm agronomy and nutrient cycling.

23. Jan 2007: Higaturu, MBE and Poliamba staff training in oil palm agronomy and nutrient cycling.
24. Mar 2007: Hargy staff training in oil palm agronomy and nutrient cycling.
25. January 2007: Steven Nake (Agronomist with OPRA) was awarded a John Allwright Fellowship to undertake a Master of Science at JCU.
26. Feb 2007 Steven Nake commenced his MSc at JCU.

8 Key results and discussion

8.1 Yield response and management options

A number of long term trials were established during the first few years of the project with the intention of 10-year life spans. It is common in oil palm fertiliser trials to take up to 5 years for yield responses to become evident. The oldest trial (Trial 144, Waisisi) is only 4 years since establishment and has not yet shown a consistent response in yield to treatments (Figure 1). It was established on a recently cleared site in order to avoid a history of Mg fertiliser application. However, leaf Mg concentrations were quite high, reflecting an initially high level of available Mg.

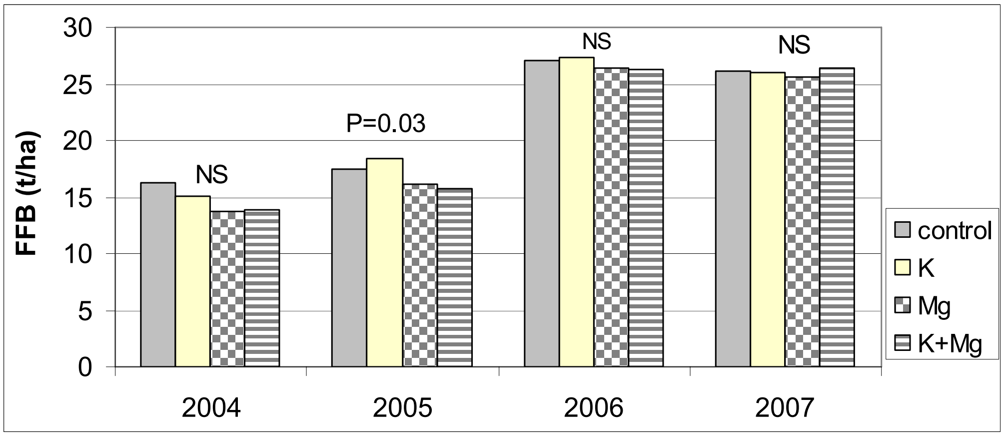

Figure 6: **Trial 144 - Annual weight of Fresh Fruit Bunches (FFB). 'NS' indicates no significant difference between treatments. Where there was a significant treatment effect, p value is shown.**

Although there has not yet been a consistent and significant yield response, the treatments are having an effect on leaf nutrient concentrations, including Mg and K (Table 5). Application of Mg significantly increased leaf Mg concentrations. Application of K significantly increased leaflet and rachis K concentrations and significantly reduced leaflet Mg. The long term trend has been for leaflet Mg concentration to fall over the last few years, with all treatments except the +Mg treatment now below the critical value of 0.20% DM in 2007. This is the first time that the control has fallen below the critical value. Rachis K concentrations in the control and both K treatments are above the critical value of 1.00% DM; however, the Mg treatment (without K) has decreased rachis K concentration to below the critical value. These results suggest that if tissue Mg and K are near their critical levels, then both Mg and K fertilisers should be added together.

In trial 145 at Walindi, there was a significant difference between the control (no Mg) and the other Mg source treatments in 2006 but not in 2007 suggesting that the treatments, which have been in place for only 3 years, have not yet resulted in yield effects (Figure 7). Unlike trial 144, trial 145 has not yet shown any differences in leaf Mg concentration between the control and Mg sources.

Trial 146 at Kumbango (Mg sources and placement) also showed no significant response in yield or tissue Mg concentrations after 3 years (data not shown).

As it is not expected that responses will become evident in less than 5 years, these trials may prove to be a valuable resource in years to come if monitoring is continued. It is encouraging that the oldest trial (T144) is now showing differences in Mg and K uptake in response to treatments. Being young palms on a new site, the Mg levels were high to begin with even the control (no Mg) having levels greater than the critical value (0.20%DM). But with time, in the Mg treatment (without K) leaf Mg levels (0.21%DM) are now just above the critical value while the treatments without Mg are well below (0.17% and 0.14% DM).

Table 5: Leaflet K, Mg, and Ca, and rachis K concentrations (%DM) for 2007; Trial 144.

Fertiliser treatment	Leaf K	Leaf Mg	Leaf Ca	Rachis K
Control	0.72	0.17	1.09	1.02
+ Mg	0.71	0.21	1.02	0.88
+ K	0.79	0.14	1.11	1.35
+ Mg + K	0.77	0.19	0.94	1.24
p (Mg)				
p (K)	0.50	**<0.001**	**0.001**	0.23
p (MgxK)	**0.007**	**0.01**	0.30	**0.006**
LSD	0.69	1.0	0.09	0.87
CV%	0.04	0.02	0.06	0.22
	4.8	9.6	5.0	17.1

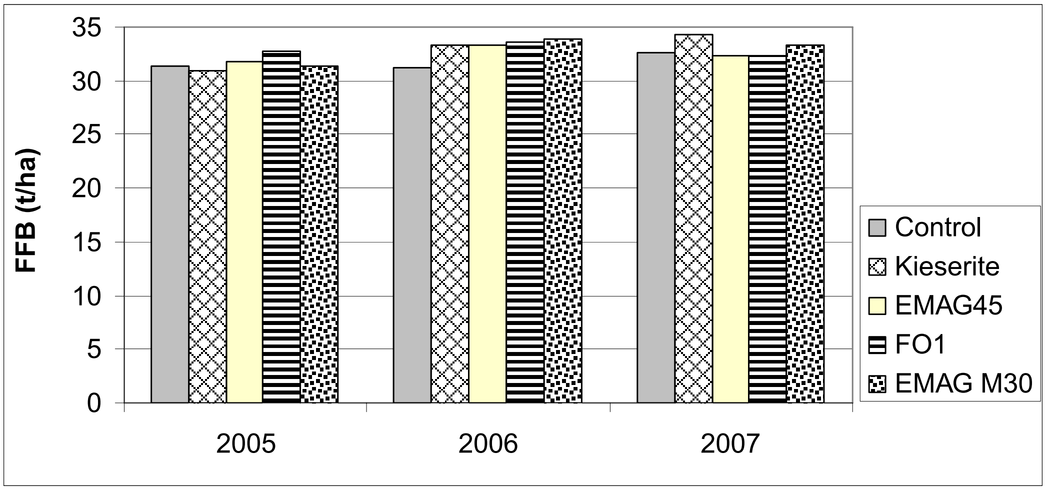

Figure 7: Trial 145; Average annual weight of Fresh Fruit Bunches (FFB) from 2005 to 2007 for the control (no Mg) and different Mg sources. The treatment effect was not significant in all years.

Another trial, this one with mature palms, has shown a substantial variation in leaf levels of Mg from year to year with averages of 0.17, 0.16, 0.22, 0.19, and 0.14%DM in the years 2003 (before treatments were imposed) to 2007 respectively. This could be a result of time of sampling (see Kraip and Webb, 2005), laboratory variations between years, or just natural year to year variation. Such variation supports the adoption of 'parallel' trials established in plantations at time of planting followed by leaf sampling at the same time as plantation sampling, and subsequent laboratory analysis with plantation and trial samples in the same batch (Webb, 2008).

8.2 Investigation of processes

8.2.1 Fate of Mg and K in the field

Fate of exchangeable Mg and K

Soil was sampled from trial 145 at Walindi in 2007 to determine the extent of Mg movement through the soil 3 years after application.

The least soluble sources (FO1, M30, EMAG45) remained in high concentrations near the surface (Figure 8). Indeed some lumps of EMAG45 were still visible on the surface. But surprisingly, even the more soluble kieserite maintained quite high concentrations in the top 1 cm. In fact, it appears that no Mg has moved more than 20 cm downwards.

However, as it was unclear exactly where the Mg had been added, and therefore unclear exactly where sampling should be done, another trial was established (Trial 151) in which fertiliser was spread carefully and evenly over the soil surface of a young plantation at Dami. After 745 mm rain the plots were sampled down to 150 cm. In this soil, which is sandier that the Walindi soil, again Mg did not appear to have moved more than 20 cm into the soil when compared with the Nil control (Figure 9). To establish that there was enough rain to move nutrient through the soil, sulphate-sulphur was also measured (Figure 11). It is quite clear that S had moved down the profile and thus there was the potential for Mg to move establishing that Mg is being strongly retained by these soils.

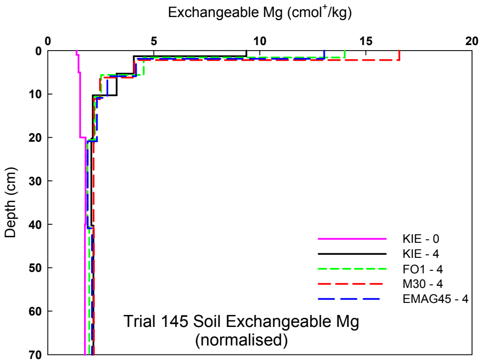

Figure 8**: Mg concentration in soil 3 years after application. Because the exact location of fertiliser application was not known, results were normalised to a common total amount above the values for Nil.**

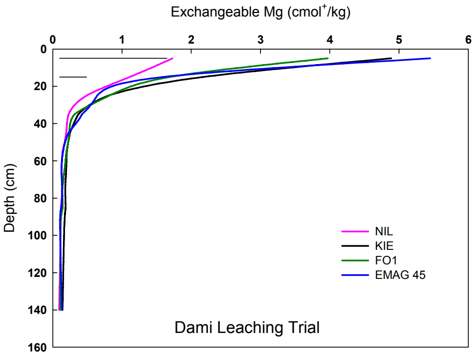

Figure 9**: Mg concentration in soil following 42 days and 745 mm rainfall at Dami (Trial 151). Where differences between treatments were significant (*p*<0.005), LSD's are shown as horizontal bars.**

Samples from Trial 151 at Dami where collected again approximately one year after the original application. Even after another 2500 mm rain (approximately), there was still little movement of Mg through the soil indicating there was very strong retention (Figure 10). A trial similar to the one at Dami was established in another volcanic ash soil at Navo. Again there was strong retention of Mg by the surface layers (Figure 12).

By contrast to Mg movement at Navo, K was easily moved through the soil and had clearly reached the bottom of the measured profile (Figure 13). Although, in contrast to S, some was retained at the surface, most likely on the exchange surface.

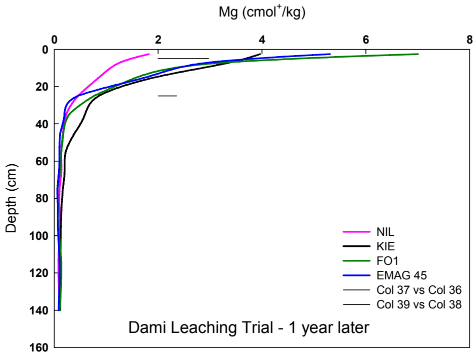

Figure 10**: Exchangeable Mg concentration in soil 1 year (and 2500 mm rainfall) after initial application at Dami (Trial 151). Where differences between treatments were significant (*p*<0.005), LSD's are shown as horizontal bars.**

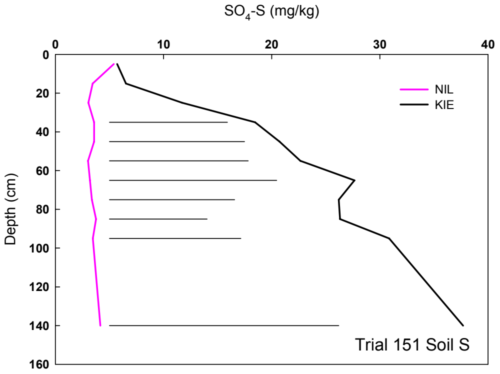

Figure 11**: Distribution of sulphate-sulphur following 6 weeks 745 mm rainfall (T151, Dami). Where differences between treatments were significant (*p*<0.005), LSD's are shown as horizontal bars.**

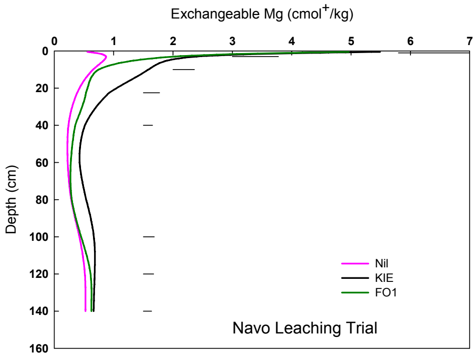

Figure 12**: Distribution of exchangeable Mg following 1156 mm of rainfall at Navo. Where differences between treatments were significant (*p*<0.005), LSD's are shown as horizontal bars.**

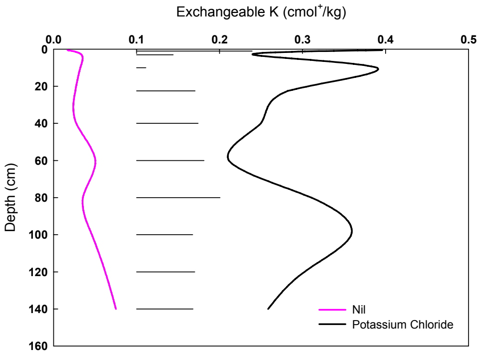

Figure 13: Distribution of exchangeable K following 1156 mm of rainfall at Navo. Where differences between treatments were significant (*p*<0.005), LSD's are shown as horizontal bars.

All forms of Mg

While it was clear that the applied Mg was being retained in the surface soil layers, exchangeable Mg did not account for all the Mg applied, so a sequential extraction was carried out on the 0-10 cm soil (Trial 151), using increasingly aggressive extractants.

Total Mg content of the control soil (by XRF analysis) was 6894 mg/kg, of which about one quarter was extracted in the fractionation procedure. Of the extractable Mg, most was in the tri-acid fraction in all plots, followed by exchangeable Mg (Figure 14). Most of the applied Mg ended up in the exchangeable fraction; 63, 74 and 63% of that applied for the kieserite, EMag45 and FO1 respectively, calculated as the difference between those plots and the nil plot. In the kieserite and EMag45 plots some of the applied Mg was recovered in the acid-extractable fractions, but total recovery of applied Mg was only 75 and 77% respectively. On the other hand, in the FO1 plot, 'recovery' of applied Mg was 151%. The reasons for the variations from 100% recovery are not yet clear, but may be due to spatial variability in application and movement of Mg.

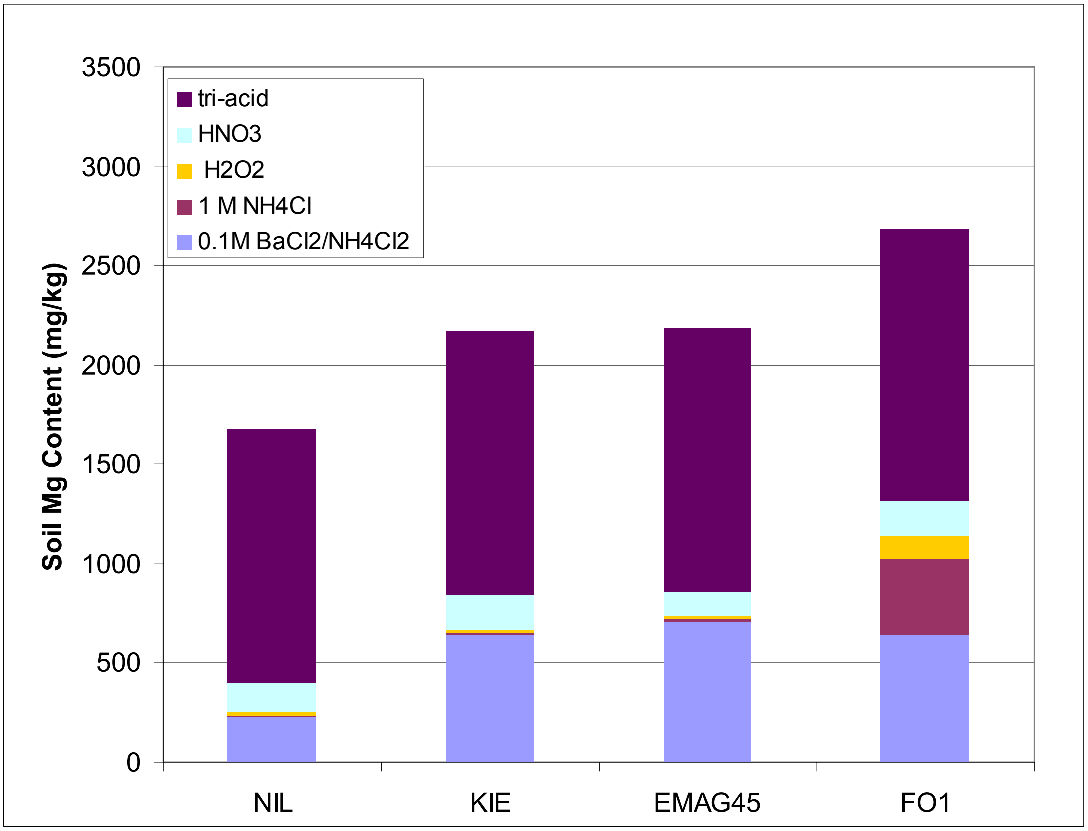

Figure 14: **Various forms of Mg, measured using sequential extractions, in soil from Trial 151 (Dami leaching trial) 42 days after fertiliser had been applied.**

Magnesium movement from fertiliser 'hot spots"

In trial 146, fertiliser was placed concentrated in trenches about 20 cm deep and 20 cm wide. Some were covered with plastic (covered) while others were not (open). Soil was then back-filled into the trenches.

In 2008, four years after the fertiliser was added, the original trenches were located and a new trench dug at right angles so samples could be taken through the original trench, and 30 and 50 cm from the centre of the original trench (Figure 15).

In both the kieserite and EMAG45 treatments a high concentration of Mg remained in the vicinity of the original trench (Figure 16). Covering fertiliser with plastic reduced the downward and sideways movement of Mg from both treatments. Without plastic, Mg from kieserite moved further than from the other fertilisers.

Figure 15: Sampling design for "hot spot" Mg placement in trial 146 at Kumbango. The dashed line indicates the position of the trench into which fertiliser Mg had been placed.

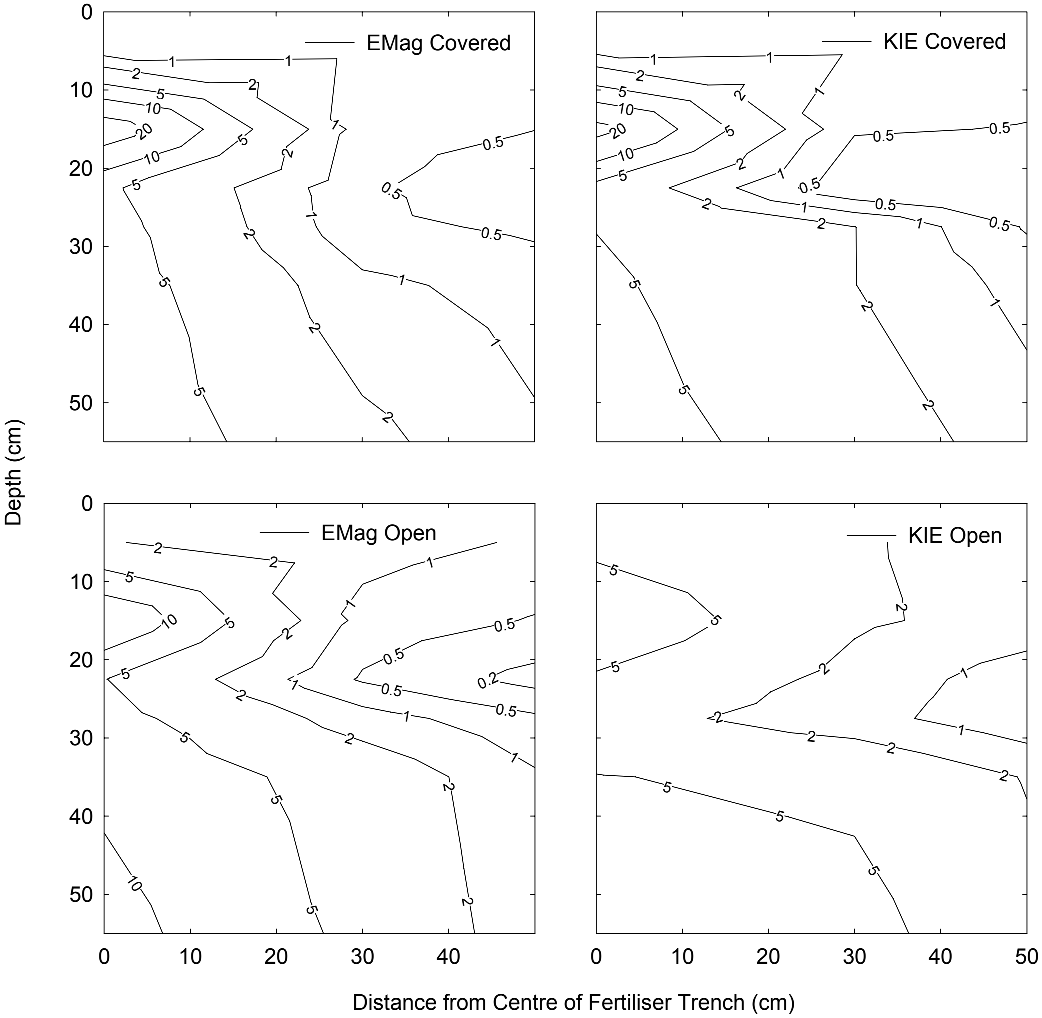

Figure 16: **"Contour plot" of exchangeable Mg concentration (cmol$^+$/kg) in four of the treatments four years after fertiliser application. The fertiliser was placed in trenches at 10 - 20 cm in depth. Emag is Emag45 and KIE is kieserite.**

Modelling Mg movement through Dami and Navo volcanic ash soils

In an effort to use modelling approaches to estimate Mg movement through soils, HYDRUS-1D was used. For this model a number of hydraulic and solute parameters need to be measured.

Determination of soil water retention parameters

Soil water retention data were fitted to the van Genuchten equation as described in the Methods. Generally there was a good fit (Figure 17) and thus a good estimate of the parameters needed to describe unsaturated hydraulic conductivity in the HYDRUS1D modelling software. A full list of parameters for each soil is given in Appendix 3.

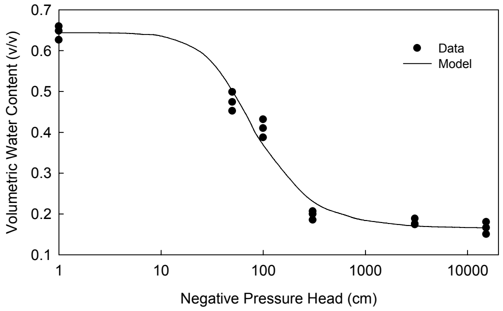

Figure 17**: Example water retention curve - Dami 15 cm depth.**

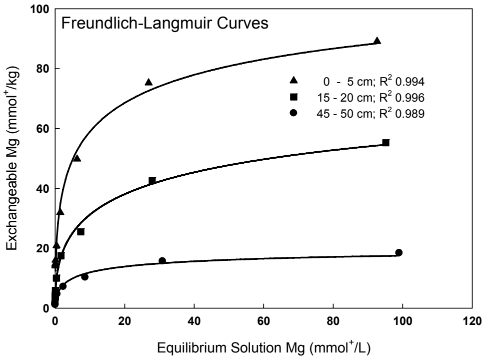

Figure 18**: Example of Freundlich-Langmuir curves for Dami soil. Note that the exchangeable Mg units (mmol$^+$/kg) are different to the way in which they are normally expressed (cmol$^+$/kg). This was necessary to keep all units the same for HYDRUS-1D.**

Determination of solute adsorption parameters

Solute adsorption parameters were determined as described in the Methods. Generally there was a good fit (Figure 18) and thus a good estimate of the parameters needed to describe adsorption of Mg and K in the HYDRUS1D modelling software. A full list of parameters for each soil is given in Appendix 3. As the shape of the curve is described by three parameters, it is difficult to visualise the effects that they have on Mg retention by soil. Thus, the results have been expressed such that they describe the resulting adsorbed Mg and K in equilibrium with a solution concentration of Mg and K (set arbitrarily to 10 mmol$^+$/L) (Table 6).

Table 6**: Calculated adsorption of Mg and K in equilibrium with a 10 mmol$^+$/L solution.**

		Freundlich Langmuir - Mg			Freundlich Langmuir - K				
Soil	Parent Material	Kd	η	β	Kd	η	β	Adsorbed Mg Concentration	Adsorbed K Concentration
		(mmol$^+$/L)	(mmol$^+$/L)		(mmol$^+$/L)	(mmol$^+$/L)		(mmol$^+$/kg)	(mmol$^+$/kg)
Bialla	Volcanic ash	26.6	0.276	0.702	4.4	0.046	0.771	56	21
Dami	Volcanic ash	40.2	0.316	0.437				59	
Kumbango	Volcanic ash	17.1	0.318	0.522				28	
Maiwara - 1	Aluvial								
Maiwara - 2	Aluvial								
Navo	Volcanic ash	18.8	0.565	0.544	1.7	0.051	0.806	22	8
Poliamba - 1	?	33.5	0.418	0.722	11.6	0.145	0.809	55	39
Ramu - 1	Aluvial								
Ramu - 2	Aluvial				30.3	0.045	0.296		55
Ramu - 3	Aluvial				61.1	0.103	0.428		128
Sagarai	Aluvial				19.0	0.043	0.671		74
Waigani - BZ	Aluvial				22.0	0.057	0.757		95
Waigani - WC	Aluvial				28.5	0.079	0.588		85
Waigani - FT	Aluvial				23.7	0.066	0.656		83
Waigani - FP	Aluvial				20.8	0.058	0.701		81
Waisisi - 2006	Volcanic ash	38.9	0.231	0.443	5.5	0.031	0.733	66	25
Walindi	Volcanic ash								
Mizzi	Sand	10.3	0.861	0.527	2.8	0.233	0.526	9	5
PinGin	Basalt	8.9	0.199	0.617	2.9	0.065	0.380	20	6

For all soils, including the Australian ones, adsorption of Mg and K was directly proportional to CEC (see section 8.2.3).

Modelling Mg movement with HYDRUS-1D

The Freundlich-Langmuir parameters, along with soil hydraulic parameters were used to model the movement of Mg (and K) through soil. Using actual daily rainfall collected near trial 151 (Dami), HYDRUS-1D was run for 42 days – the length of time since Mg fertiliser was applied and sampling commenced (Figure 19). The modelling also shows that Mg is strongly retained by the surface layers (dotted line) although it underestimates the retention. There are possibly a number of reasons for this underestimation: a) the Freundlich-Langmuir equation passes through the origin (ie 0 Mg adsorbed at 0 solution concentration) and this does not reflect the reality of Mg being retained on the exchange surface, b) the adsorption isotherms were determined with an overnight equilibration, yet it appears that there maybe slower reactions between Mg and the soil.

Using annual rainfall (2500 mm), HYDRUS-1D was used to model movement of Mg after a further year to compare with the measured data above (Figure 20). Once again there was some agreement between the model and measured data, although there again was an underestimate of Mg retention.

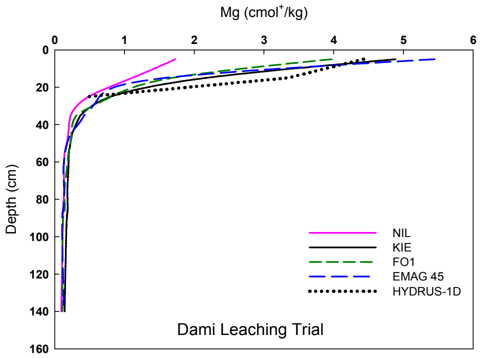

Figure 19**: Comparison of modelled data (dotted line) with measured data at Dami following 745 mm rainfall.**

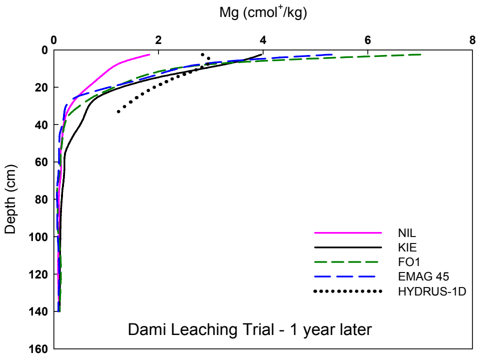

Figure 20**: Comparison of modelled data (dotted line) and measured data at Dami approximately one year after original application of Mg.**

A similar trial was conducted at Navo on volcanic ash soils with similar results (Figure 21). While the measured data showed a similar response to that at Dami, the modelled data underestimated the retention in soil at Navo even more so than for Dami. In the Navo trial sampling was done at 0-1, 1-5, 5-15 and 15-30 cm compared to the 10 cm increments at Dami. Thus the underestimation of retention (and thus greater movement) will be enhanced in the narrower surface layers.

From both sampling and modelling work it is clear that Mg is not being leached through the soil but is remaining in the surface layers.

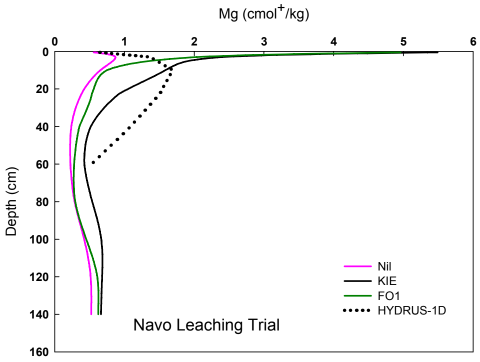

Figure 21**: Comparison of modelled data (dotted line) with measured data at Navo following 1156 mm rainfall.**

Potassium movement through alluvial soils

Trial 502b at Milne Bay Estates is a factorial trial of K, N, P, and empty fruit bunches (EFB). Part of the trial (0 MOP and 7.5 MOP at the top two N rates) was used to calculate a K budget. Knowing what rate of K has been applied over 13 years and by sampling soil from the various zones the fate of soil K was determined. Surprisingly most of the added K was in the top 20 cm with none moving below 60 cm (Figure 22). The tetraphenyl borate (TPB) extractable K represents the exchangeable plus a form that is more tightly bound in the clay matrix and is referred to as ‘fixed’. Generally, in the K-fertilised soil, TPB K it is about double that of exchangeable K and follows a very similar pattern. The means that the fixed fraction is approximately equal to the exchangeable fraction.

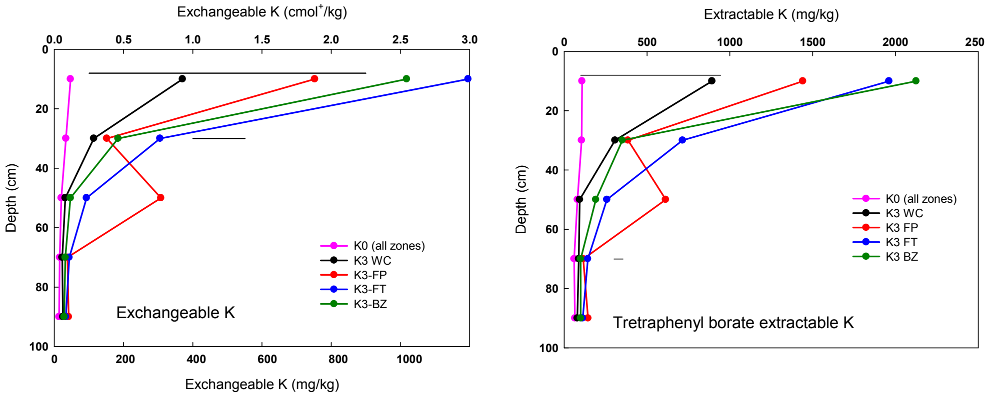

Figure 22**: Profile of exchangeable K and TPB extractable K. Where differences between treatments were significant (*p*<0.005), LSD’s are shown as horizontal bars.**

From the concentration of K (exchangeable and fixed) a total amount of K retained in the soil profile and available to palms was determined for each zone sampled. This was summed up to a hectare on the basis of the proportion of zone areas (Table 7)

Thus adding K at rate of 3.75 kg/palm/year for 13 years increased the plant available K retained in the soil by 3564 kg/ha. This was fairly even split between exchangeable and fixed K. By contrast the ratio of fixed K to exchangeable K was much higher in the soils that received no K fertiliser.

Table 7: Total amount of K accumulated due to the addition of 3.75 kg K per palm each year for 13 years (BZ, between the other zones; FP, frond pile; FT, frond tips; WC, weeded circle).

K treatment	Zone	% total area	Total soil K to 100cm Depth (kg/ha) exchangeable (Ksol + Kex)	fixed (Kf)
0 kg K/palm	BZ	69	169	397
	FP	12	39	77
	FT	3.2	8	20
	WC	10.4	27	69
Total kg K/ha			243	562
Total kg K/ha (fixed + exchangeable)			805	
3.75 kg K/palm	BZ	69	1680	1585
	FP	12	301	340
	FT	3.2	91	95
	WC	10.4	103	175
Total kg K/ha			2175	2194
Total kg K/ha (fixed + exchangeable)			4369	
Total plant available K (Ksol + Kex +Kf) accumulated in soil profile due to fertiliser addition			3564	

The amount of K sequestered and exported can also be calculated from trial data or other estimates (Table 8). Clearly the FFB is the largest component of exported K, but the amount in the standing biomass contributes substantially to this part of the K budget. The production and shedding of other components, for example the fronds pruned in any one year, were not included as it is assumed that the K in these components would be returned to the soil as they decayed.

Comparing what was added as fertiliser, with what was recovered from the soil, held in the biomass, and exported, gives the full nutrient budget for K (Table 9). There is a close relation between what was added and what was accounted for. Interestingly, more than half of the added K remains in the surface 60 cm and is not lost through leaching. What is not known is if this K is available for uptake; presumably the exchangeable K is available and the fixed K is thought to be in equilibrium with the exchangeable K (Moody and Bell, 2005). From PNG OPRA's annual report, it would appear that 3.75 kg/palm/year is more than adequate; and from this report that that K is still in the profile and available for uptake. Also importantly, some 27% of the K added is being exported in FFB. Much of this K would end up in EFB and the palm oil mill effluent (POME) ponds. Thus prudent use of EFB and POME in the field could have potential savings in costs of K fertiliser.

Table 8: Amounts of K (kg/ha) sequestered in standing palms or exported in FFB (fresh fruit bunches). The last column is the source of information; if there is no reference given, the value has been calculated from the data above it.

Planting density (palm/ha)	127	Trial information
FFB		
FFB yield (1994-2006) (t/ha)	318.9	Trial 502b database
K in FFB (kg/t FFB)	5.3	Prabowo and Foster (2006)
K in FFB (1994-2006) (kg/ha)	*1690*	
Trunk		
Trunk Height (dm)	91.3	Trial 502b database
Trunk Diam (dm)	5.15	Trial 502b database
Volume (L)	1902	
Density (19 year old palm)	0.227	Corley et al (1971)
Wt (kg)	432.5	
K concentration (%dm)	0.7	Trial 502b database
Amount K in trunk (kg/palm)	3.027	
Amount K in trunk (kg/ha)	*384*	
Fronds		
Weight (kg)	5.27	Trial 502b database (PCS)
Rachis (kg) (54% of frond dry weight)	2.83	PNG OPRA
Leaflets (kg) (46% of frond dry weight)	2.44	PNG OPRA
Rachis K (%DM)	1.55	Trial 502b database
Leaflet K (%DM)	0.63	Trial 502b database
Number of fronds on palm	41	Trial 502b database
K in Rachis (kg/palm)	1.80	
K in Leaflets (kg/palm)	0.63	
K in Fronds (kg/palm)	2.43	
K in Fronds (kg/ha)	*308*	
Roots		
K in roots (%DM)	0.65	2002 PNG OPRA Annual Report (Ambogo)
Wt Roots (t/ha)	16.2	Nelson et al (2006)
Amount K in roots (kg/ha)	*105*	
Male Inflorescence		
K in Infl (kg/palm)	0.09	Prabowo and Foster (2006)
Amount K in Infl (kg/ha)	*11*	

Table 9: Full K budget comparing what was added in fertiliser and what was recovered in soil, biomass, and export

Component	kg/ha
K added in fertiliser (3.75 kg/palm/year for 13 years at 127 palms/ha)	**6191**
K accounted for	
Accumulated in soil	3564
Standing biomass (trunk, leaves, roots, Inflorescences)	808
Exported in FFB	1690
Total	**6062**

Efficiency of potassium use

As shown above, much of the added K is not being used by the palms. In trial 502b in Milne Bay Estates the nutrient use efficiency (NUE) has been calculated in a number of ways (Goh et al, 2003): Recovery efficiency is the amount of K taken up as a proportion of that added; agronomic efficiency is amount of product produced per kg of K added; and physiological efficiency is the amount of product produced per kg of K taken up. Stepwise efficiencies relate to the efficiencies from one rate of supply to the next higher rate of supply. As expected, both recovery efficiency and agronomic efficiency decrease with increasing rates of K application. Indeed the stepwise recover efficiency at 3.75 kg K per palm has fallen to 2.7%; meaning that only 4 g of the additional 1.25 kg (3.75 minus 2.5) that was added per palm was taken up. This would suggest that 3.75 kg per palm is more than the palm needs; this is support by the accumulation of K in the soil as shown above. Physiological efficiency is less variable, suggesting that any K that is taken up is used for FFB production and that palms do not take up K in excess of requirements (Table 10).

Table 10: Nutrient use efficiency for K in Trial 502b after 13 years of K application.

	K Supply (kg/palm)			
	0	1.25	2.5	3.75
FFB Yield (kg/palm)	141	202	226	249
FFB Yield (t/ha)	17.9	25.6	28.7	31.6
K uptake (kg/palm)				
Trunk	0.05	0.11	0.17	0.19
Frond 17	0.30	0.85	1.12	1.15
FFB*	0.74	1.06	1.19	1.18
Total	*1.09*	*2.02*	*2.48*	*2.52*
Recovery Efficiency (%)		74.1	55.6	37.9
Stepwise RE (%)			37.0	2.7
Agronomic Efficiency (kg EFB/kg K)		48.5	34.0	28.8
Stepwise AE (kg EFB/kg K)			19.5	18.3
Physiological Efficiency (kg EFB/kg K)		65.5	61.2	75.8

* Fresh fruit bunches

Conclusions

Neither Mg (in volcanic ash soil) nor K (in alluvial soils) is being lost from the system through leaching. Mg is being held very tightly to the surface layers because of its affinity to the soil especially at low soil solution concentrations. Even a year after application, Mg is still retained in the surface layers. This has been shown by measurement and supported by modelling. At high rates of K application, much of the K is being incorporated into the fixed fraction and retained within the top 60 cm of soil. At these high rates only about 1/3 of the K is being taken up by the palms.

8.2.2 Plant Responses

Plant response to Mg supply were examined in the glasshouse using solution-based pot culture and also extensive field sampling and analysis of leaf tissue from a range of fronds throughout the canopy. Following the expansion phase of the project, plant response to K supply was examined in solution-based glasshouse experiments.

While the recommended optimum range for Frond 17 Mg concentration is 0.3 -0.4% for young palms (< 6 years), and 0.25-0.3% for mature palms (> 6 years) in SE Asia, experience has shown that high yields can be obtained at lower Mg concentrations in PNG.

Solution-based glasshouse experiments

Glasshouse solution culture pot trials demonstrated clear growth responses to increasing rates of Mg addition and pronounced leaf deficiency symptoms at low rates. Plant biomass and plant height reached a plateau at a solution concentration of 0.125 mmol$^+$/L of Mg (Figure 23).

In contrast, the K rate trials showed no leaf symptom development and only small reductions in growth response at the lowest rates (<0.38 mmol/L). In the soil-based omission trial, plant biomass responded to K addition in both the Bialla and Bebere soils, with exchangeable soil K levels of 0.13 and 0.28 cmol$^+$/kg respectively

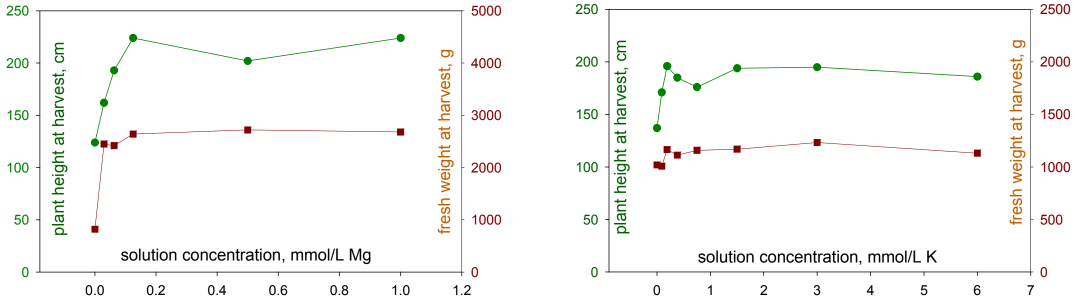

Figure 23: **Harvest data, biomass (g) and plant height (cm), for oil palm plants grown in solution culture with increasing rates of either Mg or K. The upper line is plant height and the lower line is fresh weight.**

Leaf samples were collected from the Mg rate trial on two occasions during the life of the trial and samples were analysed for leaf nutrient content and chlorophyll (a + b) (Figure 24). While leaf Mg content (%) continued to increase with increasing rates of Mg in solution, leaf yellowing symptoms, which were directly related to the chlorophyll content, changed from a Munsell colour of 7.5Y to 5GY at solution concentrations of Mg of 0.125 mmol/L and above (corresponding to a leaf Mg content of 0.085% and above). This was similar to the point where there was no further difference in plant biomass in response to increasing Mg additions (Figure 23).

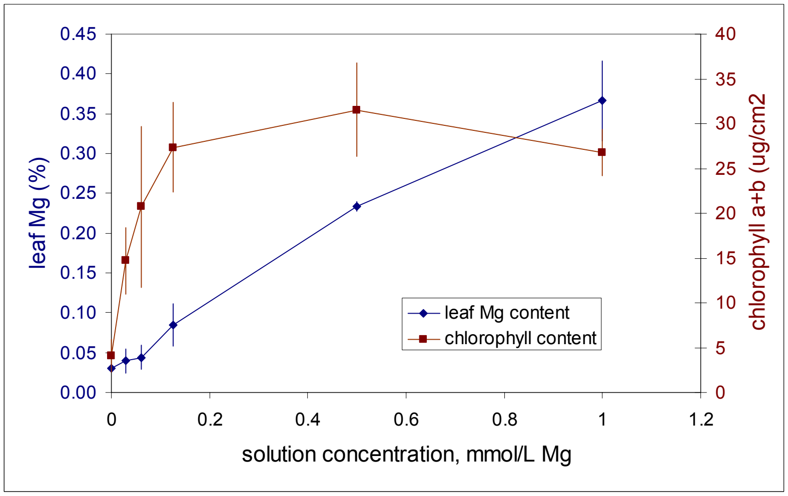

Figure 24: Relationship between leaf Mg content (%) and chlorophyll content (µg/cm^2) taken from leaflets on the 3rd and 4th fully developed frond. Error bars show the standard error of the mean.

The solution culture rate trials also clearly demonstrated the interaction between Mg and K uptake, where high levels and activity of one ion in solution reduced the uptake of the other ion (Figure 25). This data is supported by field data collected from Trial 144 (Waisisi) (Figure 26). Leaf tissue Mg concentrations increased where Mg fertilizer was applied, but were severely depressed where K fertilizer was applied. The effect of this cation competition highlights the challenge of applying appropriate rates of both K and Mg fertilizer in situations when soil has deficient levels of either one or both nutrients.

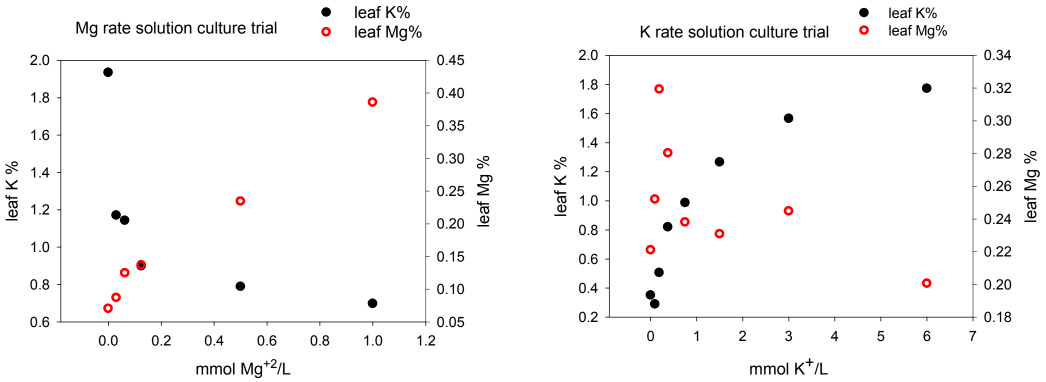

Figure 25: Competition between Mg and K uptake, where solution K concentration is constant in the Mg rate trial, and solution Mg concentration is constant in the K rate trial.

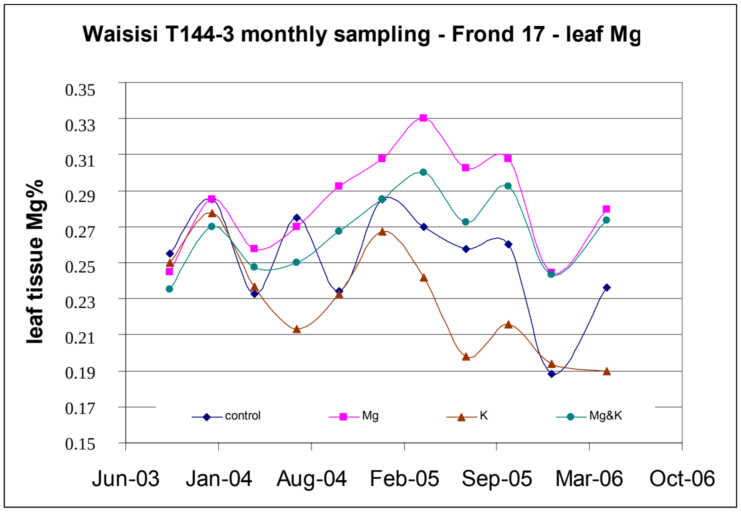

Figure 26: Leaf tissue Mg (%) in frond 17 from the control, +Mg, +K, and +Mg+K treatments in Trial 144, Waisisi. There were 4 replicates per treatment, and highly significant differences between treatments at each sampling. The least significant differences of the means at the 5% level of significance were 0.013, 0.012, 0.023, 0.030, 0.024, 0.020, 0.015, 0.017, 0.012, 0.018, and 0.038% for samples collected on Oct 03, Jan 04, Apr 04, Jul 04, Oct 04, Jan 05, Apr 05, Jul 05, Oct 05, Jan 06 and May 06 respectively.

Field leaf sampling studies

The dynamics of Mg in the palm was examined in regard to a number of factors including genotype, palm age, symptom severity, exposure to sunlight (block edge effect), seasonal variability, frond age and fertilizer input. In addition, as frond 17 is generally the most common frond used for nutrient analysis, these studies, collectively, were also used to validate the use of frond 17 as the diagnostic leaf when determining Mg deficiency.

While it is accepted that there is a relationship between symptom development and leaf Mg content, differences between progeny can make it difficult to assess how Mg uptake may relate to photosynthesis, yield, oil production and deficiency symptoms. To determine if particular Dami progeny with contrasting leaf Mg and oil extraction rate differed in Mg uptake, leaf and rachis samples (from fronds 1, 3, 9, 17 and 25) were collected from 'low Mg' and 'high Mg' Dura (D) x Pisifera (P) progenies and from 'low Mg' and 'high Mg' Dura selfs. Analysis of leaf samples indicate that leaf Mg was inherited from the Dura parent.

Commercial palms are produced from Dura (female) and Pisifera (male) parents, and DxP progeny of the Dura parent with the higher leaf Mg concentration also had a higher leaf Mg concentration (Figure 27). In contrast, leaf K concentration was the same in all progeny and Dura parents. Rachis K concentration (a better indicator of K status than leaf K in oil palms growing in volcanic ash soils) was lower in the DxP progeny than in the Dura parents. However rachis K also appeared to be at least slightly related to genotype (Figure 28).

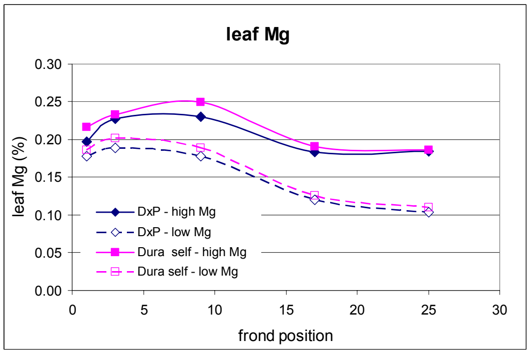

Figure 27: **Frond Mg concentration in two DxP progeny and their Dura parents.**

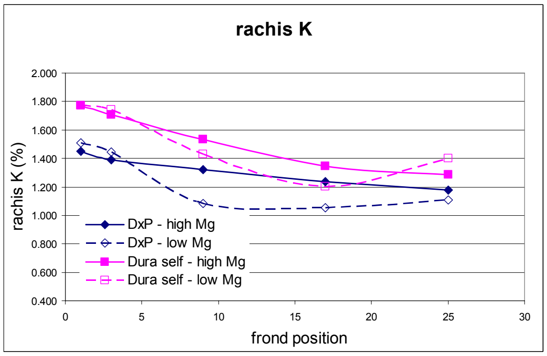

Figure 28: Rachis K concentration in two DxP progeny and their Dura parents.

Sampling of palms at Kumbango showed a considerable effect of palm age on leaf Mg concentration. (Figure 29) The difference may be partly due to changes in the mix of progenies planted over the 16-year period covered.

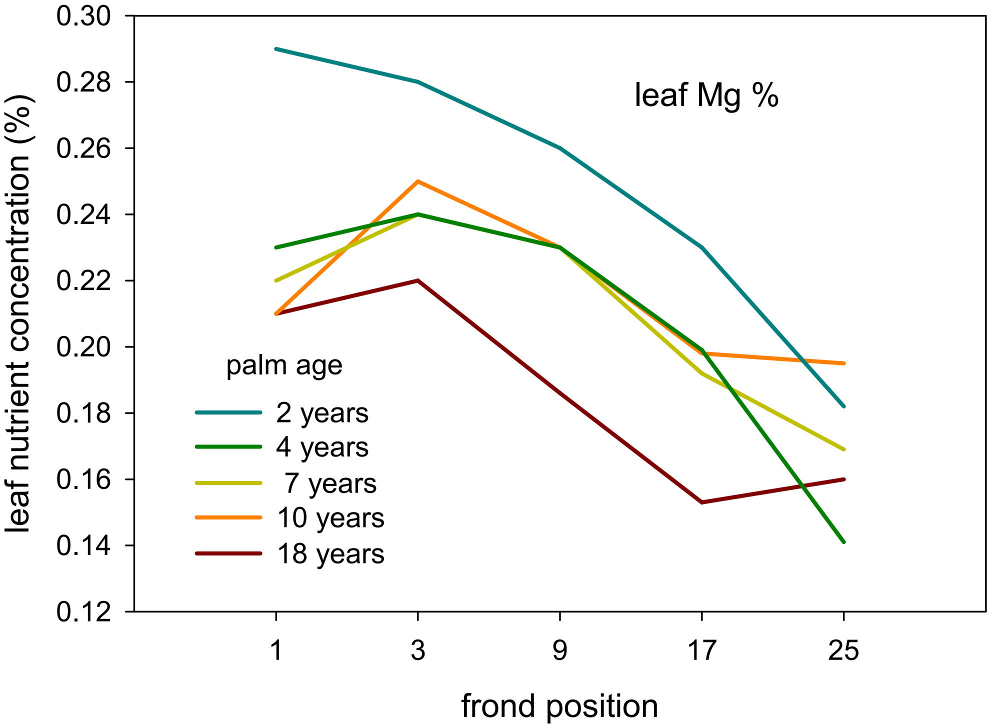

Figure 29: **Effect of palm age and frond position on leaf Mg content (%).**

A diagnostic feature of Mg deficiency is that the shaded parts of the leaf stay green while parts exposed to sunlight turn yellow. The relationship between leaf colour and Mg concentration was examined. Palms with obvious Mg deficiency symptoms had very low leaf Mg concentrations compared to palms showing no Mg deficiency symptoms (Table 11). On the palms with symptoms, leaflets from the upper rank of a frond (exposed to sunlight) were yellow and had lower Mg content than those on the lower rank (shaded) which were still green. This effect of shading needs to be taken into account when collecting leaf samples to determine Mg status as it may mask symptom development.

Table 11: Leaf tissue Mg concentration (%) from leaflets collected from the upper and lower rank from palms with and without Mg deficiency symptoms.

Palms	Leaflet position	Leaflet Mg concentration (%)			
		Bebere	Navarai	Bialla A1	Bialla A9
Palms with Mg deficiency symptoms	Upper rank (yellow)	0.016	0.019	0.033	0.038
	Lower rank (green)	0.070	0.073	0.116	0.105
Palms with no Mg deficiency symptoms	Upper rank	0.104	0.110	0.184	0.230
	Lower rank	0.151	0.161	0.185	0.240

Mg deficiency symptoms are often evident on the outside of the palms in the outer row of a block, and not on palms within the block. The relationship between these variations and leaf Mg concentrations was examined (Figure 30). Palms in the outer row of the block had lower Mg concentration in their outer fronds (facing the road) than in their inner fronds.

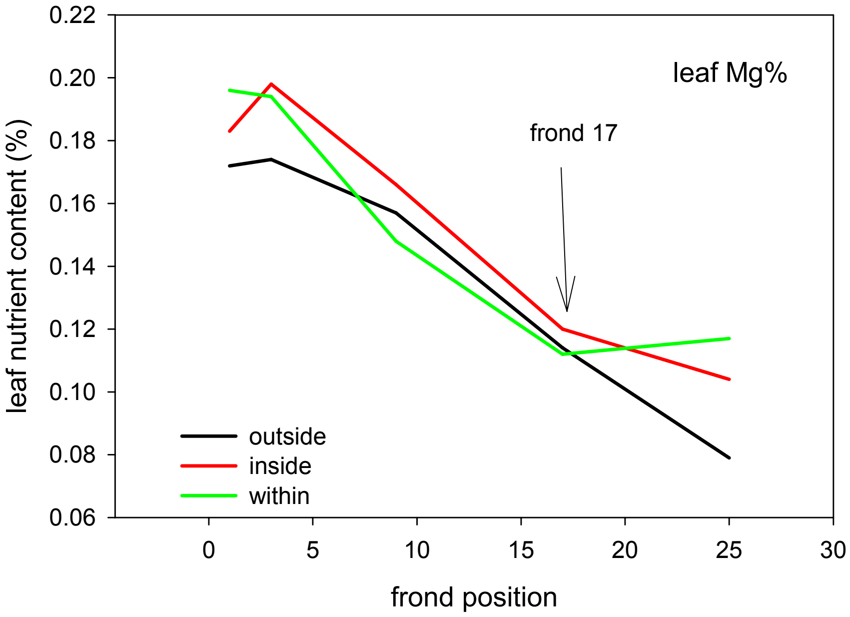

Figure 30: Effect of sampling position on leaf Mg concentration. 'outside' is fronds on outside of palms in outer row of block, 'inside' is fronds on inside of palms in outer row of block, and 'within' is fronds on palms on inside of block.

Symptom development alone may not always infer that Mg levels have reached a level that is sub-optimal for growth or yield. Trial 144 at Waisisi was rated for symptom development on three occasions. The plots receiving no Mg fertilizer had a significantly higher incidence of deficiency symptoms compared to the plots receiving Mg (Table 12), even though the leaf Mg concentrations during this period, were adequate for both the "– Mg" and "+ Mg" treatments, being on average, 0.265 and 0.315% respectively. Despite the Mg additions reducing deficiency symptom development, up to this stage of growth there had been no treatment effect on yield (refer to section 8.1 and Figure 6). In this case, symptom development may be simply associated with relocation of Mg from the older fronds to the more actively photosynthesizing younger fronds.

Table 12: Mg deficiency symptom ratings at Trial 144 (Waisisi), expressed as the number of fronds per palm showing symptoms typical of Mg deficiency.

Treatment		Fronds with Mg deficiency symptoms		
Mg	K	Jan-05	Jun-06	Aug-06
0	0	9.6	3.2	11.7
0	1	8.1	3.4	12.5
1	0	5.6	0.8	6.2
1	1	5.6	1.3	8.1
ANOVA p value	Mg effect	0.002	<0.001	<0.001
	K effect	0.384	0.334	0.228

Leaf tissue concentration of the different cations varies throughout the canopy depending on the mobility of the element. Mg and K concentrations are considerably higher in the new growth, while Ca accumulates and is found in greater concentrations in the older growth. This is illustrated by the leaf data collected from Trial 144 (Waisisi), sampled every 3 months over a period of two and half years (Figure 31). Also of note is the large variation in Mg concentration (from 0.19 to 0.29%) over this period.

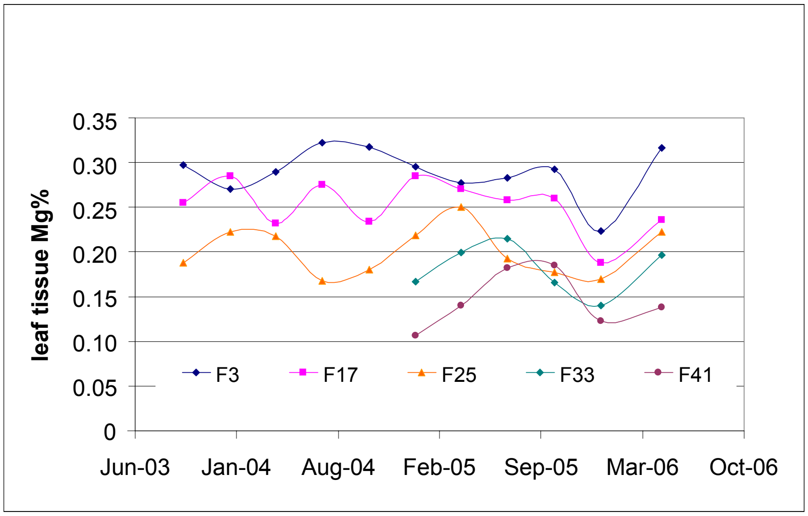

Figure 31: Distribution of Mg throughout the canopy over a 3-year period. Samples collected from fronds (F) 3, 17, 25, 33 and 41, from control treatment (no added Mg or K) in Trial 144 at Waisisi, WNBP. . There were 4 replicates of the control treatment, and highly significant differences between the leaf Mg levels of each frond sampled. The least significant differences of the means at the 5% level of significance were 0.011, 0.011, 0.020, 0.026, 0.021, 0.022, 0.017, 0.019, 0.013, 0.020, and 0.042% for samples collected on Oct 03, Jan 04, Apr 04, Jul 04, Oct 04, Jan 05, Apr 05, Jul 05, Oct 05, Jan 06 and May 06 respectively.

A productive palm normally has about 40 fronds at any one time, with all lower fronds, up to the current mature bunch, being pruned at harvest. It was hypothesised that pruning of lower fronds, particularly on young palms, may be removing a source of Mg that can be remobilized and recycled within the palm. Deficiency symptoms may appear in the younger fronds in 4-5 year old palms, when compared to older palms, because at that age demand is at mature levels, but the palms have not yet been able to accumulate enough Mg. So preventing pruning may enable them to accumulate sufficient Mg more quickly. In mature palms, lower fronds are pruned to make it easier for harvesting; but again, if these fronds are left on the palm would they provide a source of Mg which could be relocated to the upper canopy. To test this hypothesis, leaf and rachis samples were collected throughout the canopy from palms growing on smallholder blocks where there were mature palms from which the lower fronds had not been pruned. There appears to be little or no movement out of fronds older than position 17 (Figure 32). In contrast, it appears that K is continually extracted from these lower fronds.

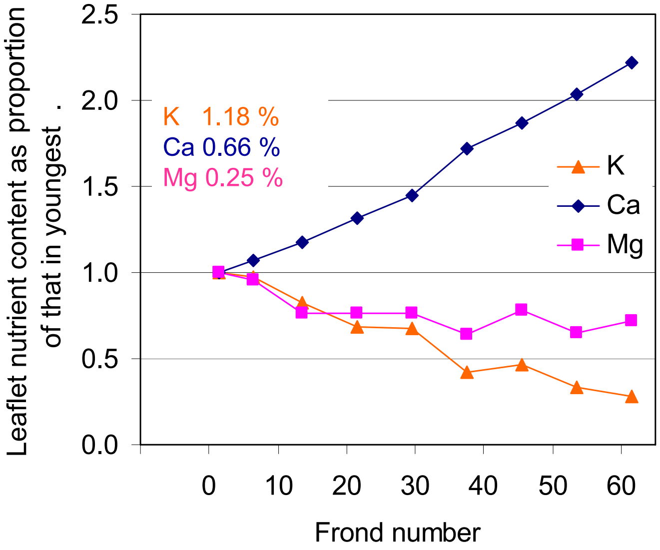

Figure 32: Leaf nutrient content of K, Ca and Mg of fronds 1, 3, 9, 17, 25, 33, 41, 58, and 64 with the nutrient content of each frond expressed as a proportion of that in the youngest frond. Actual values for the youngest frond are given. Values represent the mean from two smallholder blocks.

All of the above discussion demonstrates how leaf Mg concentrations can vary due to a number of different factors, including frond position, seasonal variation, symptom development, palm age, position in block (effect of exposure to sunlight), genotype and effect of fertilizer input and nutrient interactions. Considering this variability and how these factors can have an effect on all fronds in some way, it was concluded that frond 17 appears to be stable enough for continued use as a diagnostic frond.

8.2.3 Soil properties

The behaviour of native and applied cations in plantations, particularly uptake by plants and retention by the soil or loss by leaching, depends on properties of the soils, plants, and amendments (if applied).

Nutrient supplying capacity (omission pot trials)

Nutrient omission pot trials were used to confirm Mg deficiency independently from field trials using two soils from WNBP (Bialla and Bebere). While neither soil exhibited strong leaf Mg deficiency symptoms (Figure 33), plants growing in both soils responded to addition of Mg. In the Bebere soil, which had a soil Mg concentration of 0.3 cmol$^+$/kg (only slightly higher than the accepted critical level of 0.2 cmol$^+$/kg), biomass yield was 32% lower in the ‘minus Mg’ treatment than in the ‘complete’ treatment. The other nutrients which showed clear leaf deficiency symptoms in both soils were N, P, S and K. Plants growing in both soils had > 30% less biomass in the ‘minus K’ treatments than in the ‘complete’ treatments.

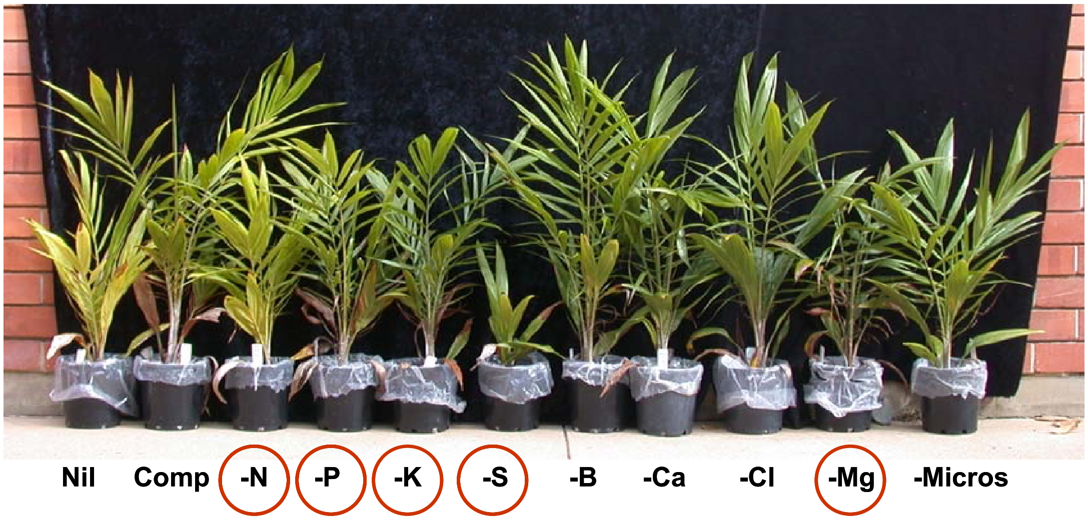

Figure 33: **Nutrient Omission trial in soil from Bebere (WNBP). "Nil' means no nutrients applied and 'Comp' means all essential elements supplied.**

Mineralogy and chemical properties of soils

The volcanic ash soils of West New Britain are recent, being formed in tephra deposited 0-5000 years before present. They are often distinctly layered, with pumice alternating with finer ash. Their mineralogy was determined, and was consistent with their age, showing little weathering; mostly dominated by glass (the major amorphous material) and feldspar, and having relatively low contents of the clay minerals allophane, halloysite or smectite (Table 13). As well as glass, crystobalite was detected in many samples. Both materials are indicators of rapid cooling of magma, consistent with their volcanic ash origin. The main feldspar appeared to be anorthite, which is Ca-rich, related to the high contents of Ca in these soils.

The contents of total and exchangeable Ca, Mg, K and Na in the volcanic ash soils of West New Britain was related to the origin and weathering of the tephra. The total contents of Ca, Mg, K and Na were closely related to the origin of the magma as determined by source indices (Figure 34). The source indices were related to the depth of the subduction zone, determined from depths of earthquake foci. The closer to the subduction zone, the lower the content of Mg relative to total cations and the higher the relative contents of K and Na. In all soils Ca made up about 40-50% of cations. The relationships between cations and magma source held only for the West New Britain soils, which had similar origin, and not to the volcanic ash soils in Oro (Figure 34).

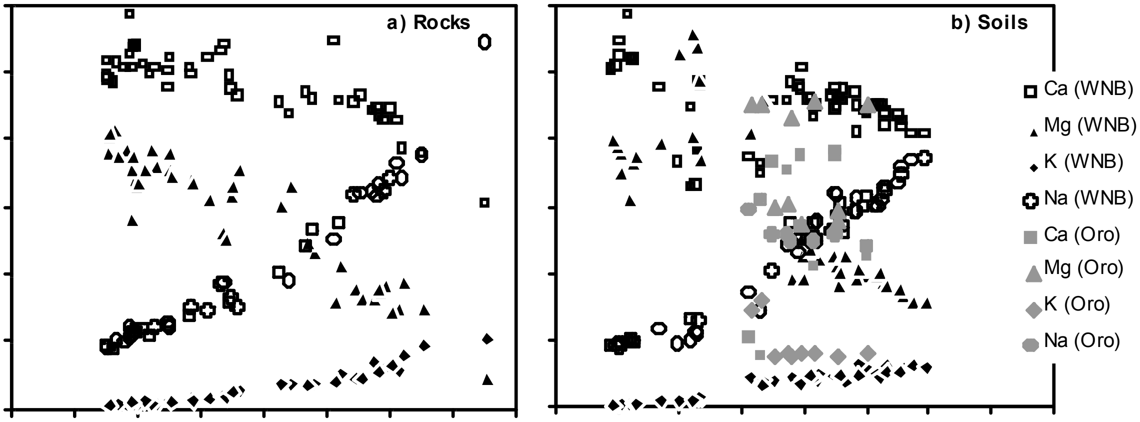

Figure 34: Content of Ca, Mg, K and Na (as a % of total cation content) as a function of tephra source index (Differentiation index, SIa) for a) rocks from around Witori and Ulawun volcanoes in West New Britain (data from Blake and Ewart, 1974 and Johnson et al., 1972) and b) the soils from West New Britain (WNB) and Oro analysed in this work.

As the West New Britain soils have weathered their total cation contents have declined, especially Ca, but their exchangeable cation contents have increased and the exchange sites have become increasingly dominated by Ca relative to K and Mg (Figure 35). The release of Ca from minerals into solution during weathering explains why these soils have such high exchangeable Ca contents and such high ratios of exchangeable Ca to Mg and K. Comparing the West New Britain soils to the Oro soils shows that the West New Britain soils generally had lower exchangeable Mg percentage than the Oro soils. Exchangeable K percentage was similar in soils from the two provinces and tended to increase with depth (Figure 35). The West New Britain soils had reasonably high CEC, considering their generally unweathered nature and low clay contents. Their CEC was related to organic matter content and degree of weathering (21 and 28% of variation, respectively).CEC generally decreased less with depth in the West New Britain soils than in the older volcanic ash soils of Oro Province (Figure 36), indicating that in the more weathered soils the CEC was more closely related largely to organic matter content, as is typical in weathered tropical soils.

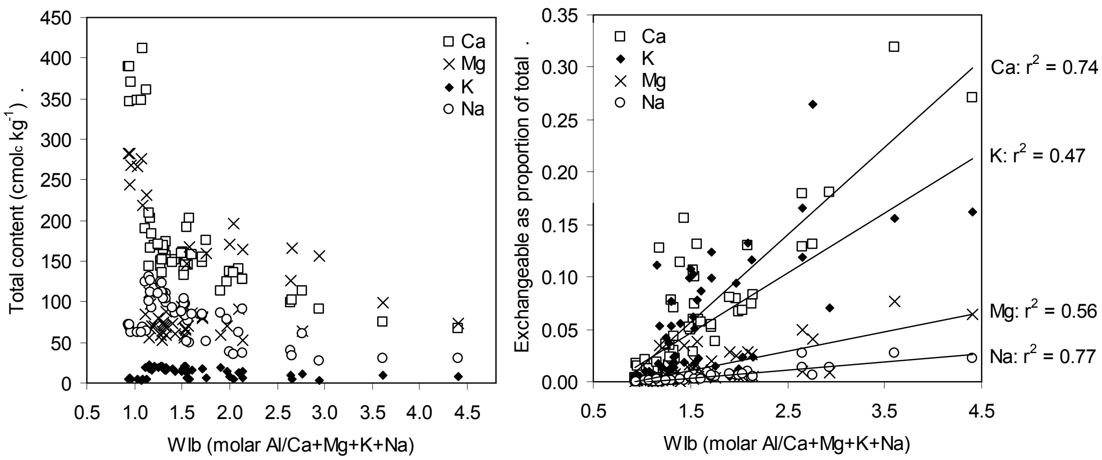

Figure 35: Total cation contents (a), and exchangeable cation contents as a proportion of total cation contents (b), as a function of weathering (weathering index, WIb) for West New Britain soils.

Cation exchange capacity of the volcanic ash soils was also greatly influenced by management. Analysis of surface soil from different management zones in T129 showed a four-fold difference in CEC between the soil in the weeded circle, where no plant residues are applied, and the soil in areas where pruned fronds or EFB had been applied (Table 14). Application of fertiliser caused acidification and a considerable decline in CEC, more than halving CEC in the weeded circle and frond pile (Table 14).

Most of the soils analysed had high organic C contents and favourable pH values (generally >5.2). In the volcanic ash soils of West New Britain, organic C content was related to depth and the content of allophane or poorly crystalline Fe oxides (43 and 12% of variation, respectively). The content of poorly crystalline Fe oxides was related to source and degree of weathering of the tephra and to allophane content (51, 10 and 8% of variation, respectively).

The alluvial and coralline soils were quite different to the volcanic ash soils. The well-structured alluvial clay soils of Ramu and Milne Bay were dominated by vermiculite or smectite (Table 13), both of which can fix K. Consistent with their clay content and mineralogy they had high CEC (35-60 cmol$_c$/kg throughout the profile). Exchangeable cations in both provinces were dominated by Ca and Mg (about 60% and 40% of exchangeable cations, respectively). The red clay soils over coral in New Ireland were highly weathered, being dominated by kaolinite (Table 13) and had low CEC, less than 8 cmol$_c$/kg throughout the profile. Exchangeable cations in those soils were dominated by Ca at the surface and acidic cations at depth.

Table 13**: Soil mineralogy.**

Site	Depth (cm)	Amorphous	Feldspar	Kaolin (Halloysite)	Smectite or Vermiculite	Allophane	Fe oxide[1]
Volcanic ash soils (West New Britain)							
1. Navarai	0-13	++++	++	-	-	+	+
	79-100	(++++)	(++++)	++	-	+	+
3. Haella	0-16	++++	++	-	-	+	+
	92-100	++	++	++	++++	+	+
4. Kumbango	0-12	++++	+++	-	-	+	+
	94-127	++++	++	-	-	+	+
6. Dami	0-19	(++++)	(++++)	-	-	+	+
	101-114	++++	+++	-	-	-	-
7. Malilimi	0-16	++++	++	-	-	+	+
	77-97	++++	+	-	-	+	-
8. Bilomi	0-10	++++	++	-	-	+	+
	88-110	++++	+++	-	-	++	+
10. Bialla	0-26	(++++)	(++++)	-	-	++	+
	72-107	++++	++	+++	-	++	+
11. Balaha	0-20	(++++)	(++++)	-	-	++	+
	72-108	++	(++++)	(++++)	-	++	+
12. Navo	0-9	+	++++	-	-	+	+
	100-117	+	++++	-	-	++	+
Alluvial soils (Milne Bay and Morobe)							
Waigani T502	15-20	+	+++	+	++++	nd	nd
Sagarai T504	13-18	+	+++	+	++++	nd	nd
Ramu Bl409	15-20	+	-	-	++++	nd	nd
Ramu Bl202	20-25	(++++)	+	-	(++++)	nd	nd
Soils developed over coral (New Ireland)							
Poliamba	40-45	-	-	++++	-	nd	+

++++ >60%, +++ 20-60%, ++ 5-20%, + <5%, parentheses indicate co-dominance of two mineral types, - trace or not detected, nd not determined

[1] Poorly crystalline Fe oxides in the volcanic ash soils, goethite in the coralline soil

Retention of added cations, and cation exchange selectivity

The ability of the soils to retain added Mg or K was determined by establishing adsorption isotherms. The ability of all soils to retain the added cations was directly proportional to their CEC (Figure 37).

All of the volcanic ash soils were dominated by exchangeable Ca, so competition between Mg or K and Ca may determine uptake and leaching losses of Mg and K. Competition between cations for exchange sites is called exchange selectivity, and can be measured in two ways. In the first, the relative amounts of cations in solution and on exchange sites is measured. If a particular cation makes up a higher proportion of exchangeable cations than soluble cations, then it is preferentially adsorbed. The Gillman soil sample set was analysed for cation concentrations in solution as well as exchangeable cations. All soils from all depths retained Ca approximately twice as strongly as Mg (Kerr selectivity coefficient of ~2). The relationship between exchangeable and solution K was much more variable. The Gapon selectivity coefficient for Ca/K exchange was related to soil organic C content, pH and origin of the magma (51% of variation together).

The exchange selectivity of the soils was also determined in binary systems (Ca/Mg or Ca/K) in the laboratory, using constant ionic strength. The results confirmed those from natural contents of exchangeable Ca, Mg and K described above. Mg was adsorbed approximately half as strongly as Ca, irrespective of soil type or depth (Figure 38.) Exchange selectivity was influenced by the anion present. Chloride induced poorer adsorption of Mg relative to Ca than did nitrate. K was adsorbed less strongly than Ca, due to valence, but the exchange coefficient varied with soil type and sampling depth. The higher the soil organic matter content the less strongly K was adsorbed relative to Ca (Figure 39).

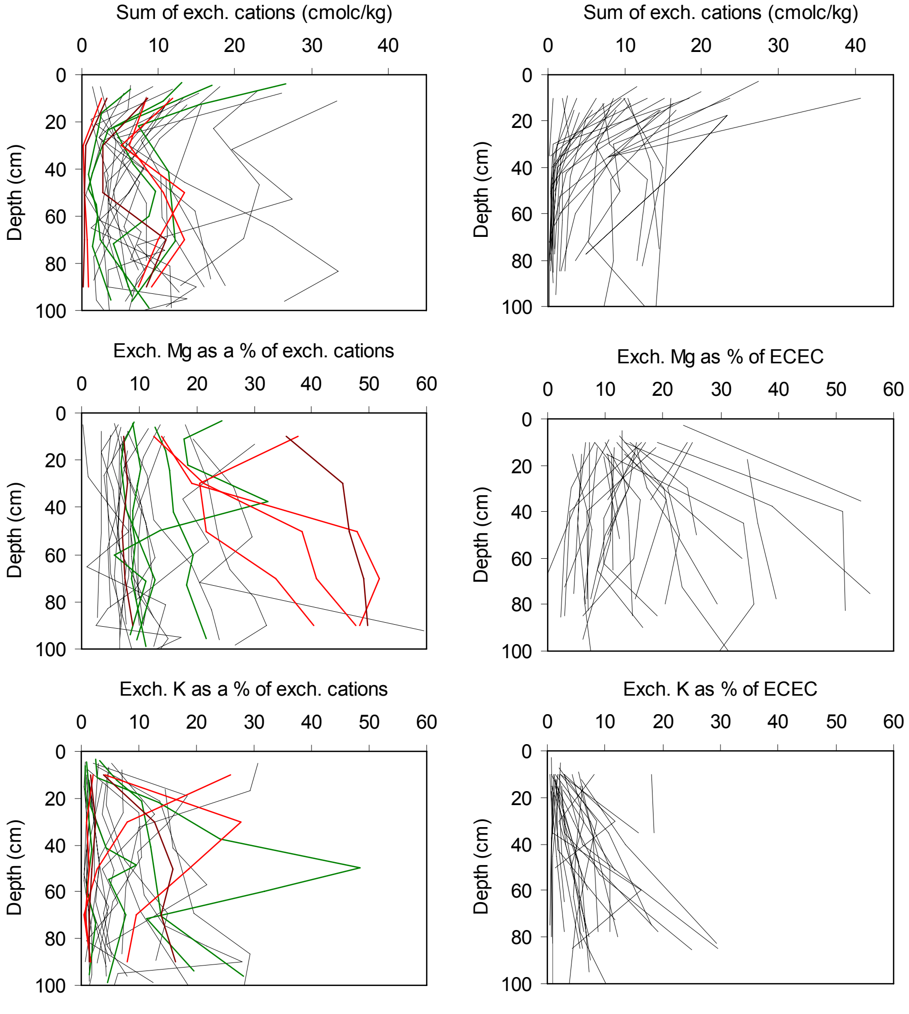

Figure 36: **Cation exchange capacity and exchangeable Mg and K percent in soils from West New Britain (left side-Gillman set, black and green lines) versus Oro Province (right side-smallholder set and red and brown lines in left side graphs).**

The cation exchange selectivity measurements suggested that Mg might be lost by leaching from volcanic ash soils, due to its poor competitiveness for exchange sites compared to Ca. However, the measurements of Mg leaching in the field showed that the soils had adequate CEC to retain Mg near the surface irrespective of preferential Ca adsorption. Similarly, although K losses by leaching might be expected in a soil dominated by exchangeable Ca and Mg, K was retained near the surface in alluvial soils with high CEC.

Table 14**: Cation exchange capacity (cmol$_c$/kg) of soil (0-5 cm depth) from different management zones and with different history of fertiliser application (ammonium chloride and kieserite) in Trial 129.**

Management zone	Fertiliser not applied	Fertiliser applied
Weeded circle	6.5	2.9
Frond pile	28.4	10.1
Between zones (with EFB)	26.5	22.8
Between zones (no EFB)	10.1	

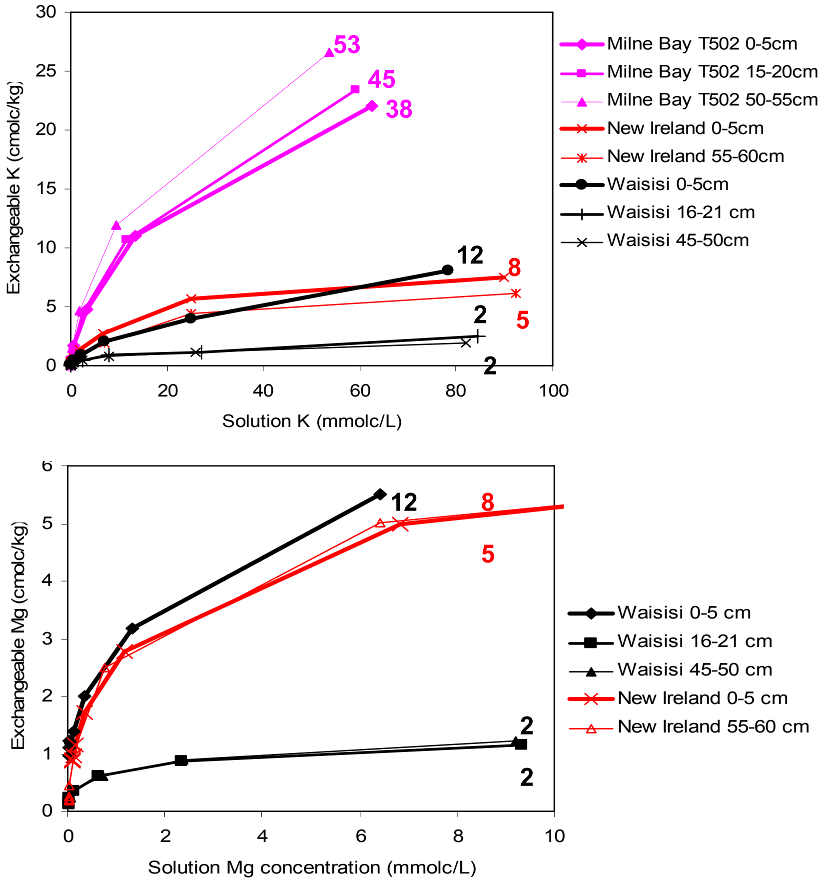

Figure 37**: Adsorption isotherms for Mg and K in several volcanic ash (Waisisi), alluvial (Milne Bay) and coralline (New Ireland) soils. Figures in the graphs are the soil CEC values (cmol$^+$/kg).**

Soil hydraulic properties

There is a high potential for loss of nutrients by leaching in oil palm growing areas due to high rainfall and permeable soils. Rainfall ranges from approximately 2000 to 4000 mm per annum, and oil palm transpires approximately 1300 mm per annum, leaving approximately 700-2700 mm to be lost by deep drainage or runoff. Runoff loss is very low on the permeable volcanic ash soils (Banabas et al, 2008), resulting in high leaching potential. In this project we measured infiltration rates and water retention curves on a range of soils.

Infiltrability was generally very high, but covered a wide range of values (Figure 40). In the volcanic ash soils infiltrability was >100 mm/hour at all sites and depths apart from the surface measurement at one site at Kumbango. The coralline soil (Poliamba) and several of the alluvial clay sites had low infiltrability (<100 mm/hour) at depth. Water retention curves also differed widely between sites (Figure 41), although high porosity and high water contents at saturation were common (bulk density as low as 0.68 Mg/m^3 at the surface in some volcanic ash soils).

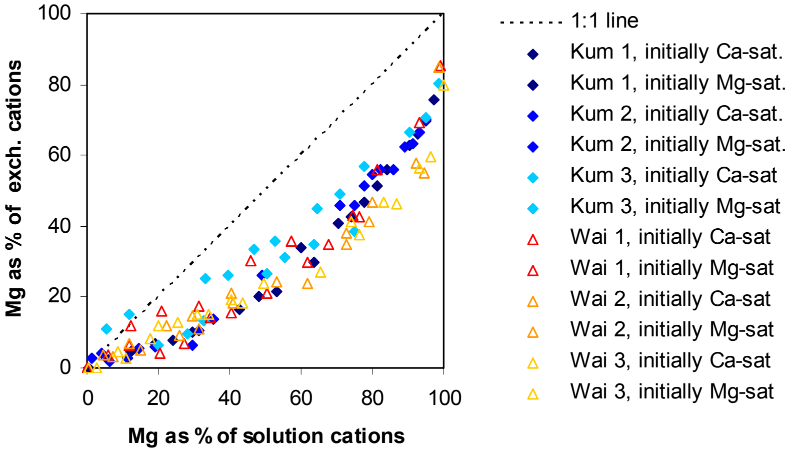

Figure 38: Exchange selectivity isotherms for Mg/Ca , showing little or no difference between different soils (Kumbango and Waisisi), depths and organic matter content (indicated by 1, 2 and 3) and direction of exchange measured following initial saturation with either Ca or Mg.

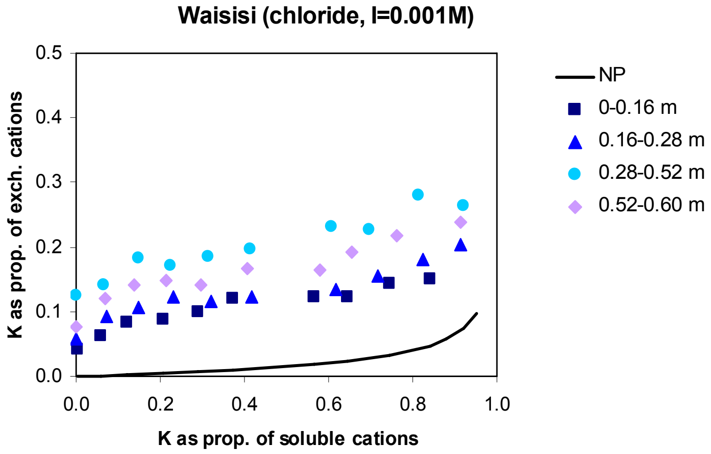

Figure 39**: Exchange selectivity isotherm for K/Ca in Waisisi soil from a range of depths. 'NP' is the non-preference isotherm, taking cation valence into account.**

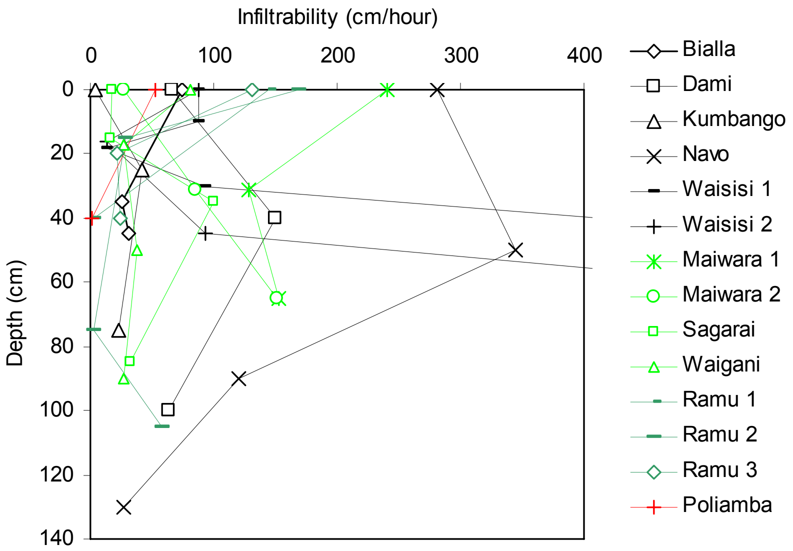

Figure 40: **Saturated infiltration rates in volcanic ash (black), alluvial (green) and coralline (red) soils.**

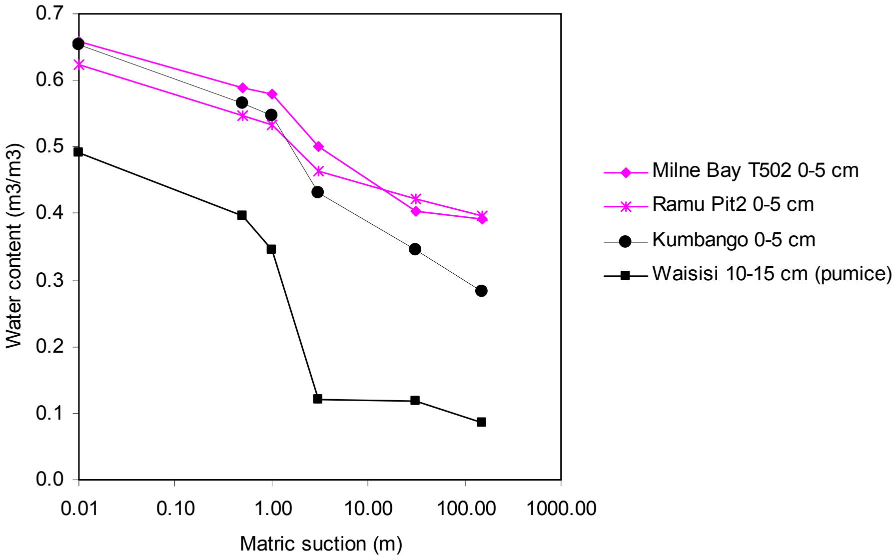

Figure 41: **Water retention curves in the finest (Milne Bay and Ramu alluvial soils) and coarsest (Waisisi pumice) textured soils examined and a clayey volcanic ash soil (Kumbango).**

8.2.4 Amendment properties

Kieserite is the traditional source of Mg used in PNG. Although the name kieserite originated with mined material, the kieserite currently used is produced by reaction of $MgCO_3$ with H_2SO_4. It is soluble and contains about 17% Mg (Table 15). The Mg source with lowest solubility was MgO. Magnesite also had low solubility and Silvine had moderate solubility. Due to its high Ca content, dolomite would only be considered in areas such as the Ilimo-Paki and Mamba areas of Oro Province, where all cations are in low supply. Speciation modelling was carried out to determine what proportion of Mg existed as Mg2+. For kieserite at the concentrations reached just below the application zone, up to 50% of Mg could be in $MgSO_4$ ion pairs. $MgSO_4$ could be susceptible to leaching loss. However, a decrease in concentration, which would occur after subsequent rainfall and leaching, causes a rapid decline in the proportion of Mg as $MgSO_4$, so this would not appear to be a problem. A sand culture experiment was carried out in the glasshouse to assess the uptake and leaching loss of Mg from the different sources. Results corresponded with the solubility values shown in Table 15, with large losses of kieserite by leaching but negligible loss of the other amendments.

Table 15: **Properties of the main amendments used.**

Amendment	Main constituent	Mg content (%)	K content (%)	pH	Solubility (mg Mg/L after 24 hours)
Kieserite	$MgSO_4.H_2O$	17	0	~9.0	>230,000[1]
FO1® (magnesite)	$MgCO_3$	26	0	10.1	4.6
M30®	$MgCO_3/MgO$	42	0	10.7	2.7
EMAG45® (magnesia)	MgO (90% <45 µm)	55	0	11.7	0.2
EMAG500® (magnesia)	MgO (90% <500 µm)	55	0	11.7	0.4
Olivine	$(Mg,Fe)_2SiO_4$	19	0	8.8	5.5
Silvine® (acid-treated olivine)	-	21	0	5.8	341.3
Dolomite	$(Mg,Ca)CO_3$	5-20	0	nd	nd
Muriate of potash (MOP)	KCl	-	50	nd	nd
EFB[2]		0.13	2.32	nd	nd

[1] calculated using speciation model
[2] Nutrient content is % of dry matter, which is ~10-30% of fresh weight

nd = not determined

8.3 Integration

8.3.1 Predicting Mg and K movement

Bringing together information on water retention, bulk density, and Mg and K adsorption properties of the soil profile layers (see Appendix 2), together with rainfall information and fertiliser application rates, it is possible to predict Mg and K movement at a number of locations (Table 3) under various seasonal patterns.

For example given the same amount of Mg fertiliser and the same rainfall pattern, the simulation predicts that the movement through soil profiles from Dami, Kumbango, and Bialla would be quite different (Figure 42).

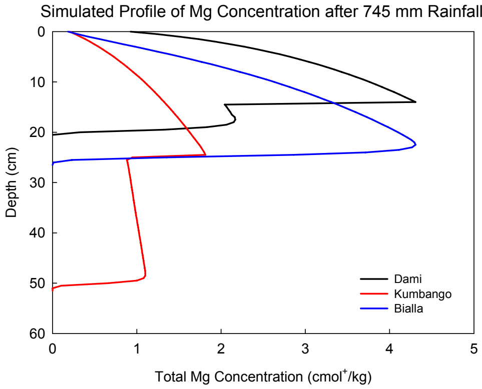

Figure 42: **Profile of Mg distribution following 745 mm rainfall in three locations in WNBP.**

Such information will allow managers to simulate the effects of different amounts of fertiliser application and different patterns of fertiliser application in relation to rainfall intensity, frequency, and timing.

We have also modelled the effect of physical barriers to prevent soil water moving through the fertiliser. In trial 141, K was packed into half coconut shells turned upside down and buried about 20 cm below the soil surface. The model shows (Figure 43) that soil water is defected around the K fertiliser by the shell and being protected from leaching.

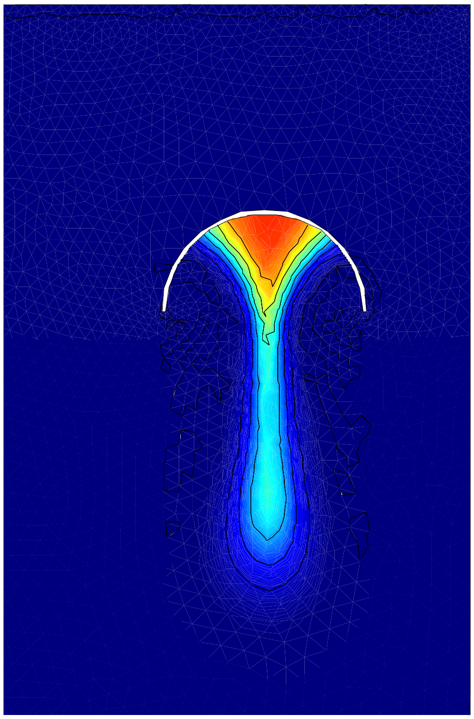

Figure 43**: Modelled effect of a coconut shell barrier protecting K fertiliser from soil water leaching; modelled with HYDRUS-2D (Simunek et al., 1999). Red to blue represents high to low concentration of K.**

8.3.2 Predicting regions of Mg and K deficiency

Although we have tools to predict the fate of Mg and K fertilisers as shown above, many smallholders do not use sufficient quantities of fertilisers to even replace nutrient exports in FFB. Thus the soil type or region will dominate the likelihood of deficiencies appearing.

Maps of leaf nutrient levels provide a sense of the nutrient status of smallholder palms in a particular area. The maps below demonstrate that there are clear clusters of nutrient status. Clearly K leaf levels are somewhat higher in the northwestern edge of Sarakolok and Mai districts, than they are in the Siki district (Figure 44). This is consistent with soil K levels; the nil fertiliser plots at Waisisi (which is near Siki) had much lower exchangeable K than the nil fertiliser plots at Kumbango (which is near Sarakolok) (see Appendix 2).

The distribution of leaf Mg values was not as consistent as it was for K. In both the Sarakolok and Mai districts leaf Mg levels ranged from low to high (Figure 45). By contrast, in the Siki district the Mg levels were generally low. However, they also consistent with results of sites 4 (west) – 6 (east) in the batch of samples collected by Gillman and Gillman (2001) which show an increase in Ca/Mg ratio from west to east.

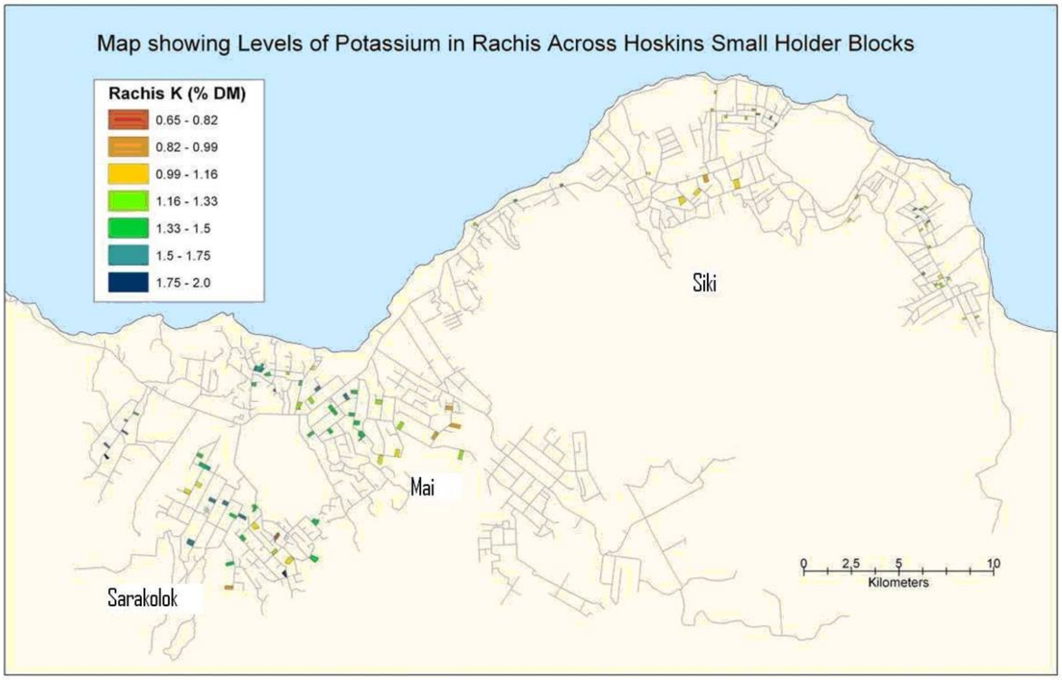

Figure 44**: Distribution of leaf K values for some selected smallholder blocks**

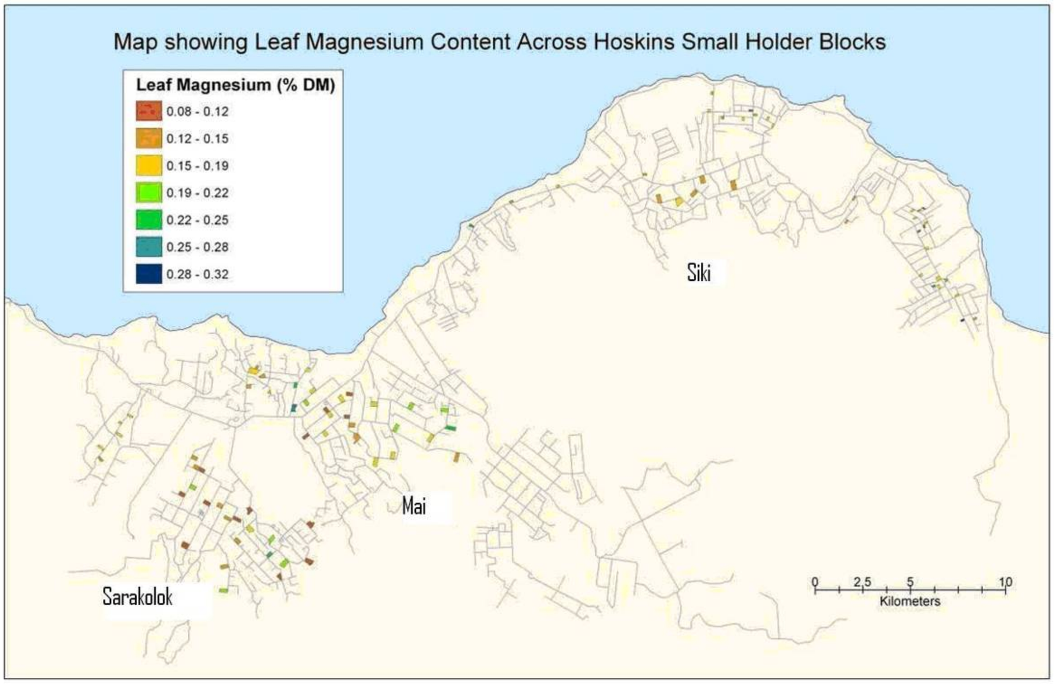

Figure 45**: Distribution of leaf Mg values for some selected smallholder blocks**

8.3.3 Improved fertiliser recommendations for smallholders

This project also contributed to an Agricultural Innovations Grant Facility (AIGF) project to provide site specific fertiliser for smallholders (Rogers et al, 2006 a&b). Previously, there was a single recommendation for all smallholders associated with each nucleus estate; irrespective of local conditions. By combining spatial data on soil type with fertiliser recommendations for nearby plantation blocks, block specific fertiliser recommendations were made. These are available both in a spatial form (Figure 46) and in tables.

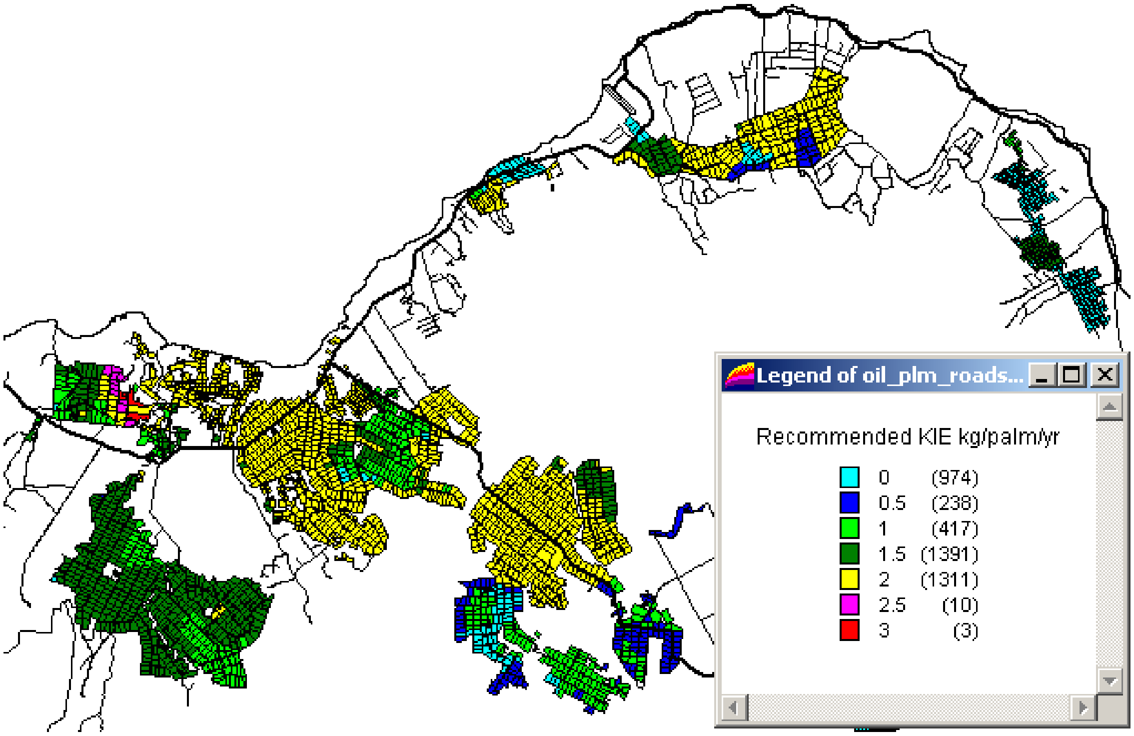

Figure 46**: Mg fertiliser Recommendations for smallholders in the Hoskins Project region**

9 Impacts

9.1 Scientific impacts – now and in 5 years

Most of the scientific impacts of the work will be felt in the next 5 years, as the most important results have been found near the end of the project and are yet to be published. However, some scientific impacts have already been made.

When our research plan became known, Lonsum, a highly successful oil palm company in Indonesia, also started trials with the alternative Mg-containing amendments that we proposed (magnesium carbonate and magnesium oxide).

The following discoveries are expected to have considerable scientific impact within the next 5 years:

- Field trials and glasshouse solution culture trials have demonstrated the interaction between Mg and K supply and plant uptake of K and Mg.
- Cation distribution through the canopy has been related to genotype.
- Oil palm has been successfully grown in solution culture.
- Tissue cation concentrations, symptoms and yield responses have been related to solution concentrations.
- Soil properties have been related to the source and weathering of the ash.
- Solute transport model simulating the experimental results has shown a close match with actual results
- Both experiments and modeling provide evidence that Mg not lost by leaching.
- The unexpected result that Mg is being held quite strongly in the surface layers of volcanic ash soils will change the way scientists think about these soils.

9.2 Capacity impacts – now and in 5 years

As a result of this project, PNG OPRA Agronomy staff have a greater understanding of Mg and K nutrition of oil palm. They have also learnt new techniques such as measuring infiltration rates of water into soil, collecting soil for bulk density measurements, conducting nutrient omission pot trials, establishing non-conventional field trials, and assessing and documenting Mg and K deficiencies in palms.

OPIC extension officers and plantation managers have benefited from a number of workshops on soil science and plant nutrition, and students from Vudal University and University of Technology have benefitted from hands-on experience in research.

As it was agreed that PNG OPRA would continue the field trials related to this ACIAR project well after the project finished, the skills identified above will be further developed as well as learnt by new staff. The workshops above, which were initiated by this project, have been made a regular feature of PNG OPRA's service to the oil palm industry and will continue to be into the foreseeable future.

A full list of training activities was presented in section 7.1.5

9.3 Community impacts – now and in 5 years

Currently, it is primarily a lack of N that is limiting oil palm production by many smallholders. Thus the benefits of Mg and K will not be realised until N nutrition is improved. Because there is an expense in purchasing N, farmers need to be convinced that it is worthwhile. This project's contribution to the AIGF project ('Site specific fertiliser recommendations to increase income of smallholder oil palm producers in West New Britain Province') will provide some of the confidence to farmers of the benefit of balance nutrient supply. By linking site-specific fertiliser recommendations with OPIC's site-specific Cash Management Plan, smallholder families will benefit from greater incomes during the next few years.

9.3.1 Economic impacts

As described above, over the next few years, from an interaction of the related AIGF project and OPIC's Cash Management Plan, family incomes will slowly increase as the production benefits of balanced nutrition are realised. Part of this increased income will be re-invested in appropriate fertilisers and thus continue to increase production and family incomes.

Smallholders in the Ilimo Division of Oro province began using K fertiliser during this project. There are over 550 smallholder blocks in that division (>2,000 ha). Growers using fertiliser can expect 5 t/ha extra FFB yield per year, which at K200/t FFB, K2,363/t MOP and K1,041/t AC equates to an extra income of K487/ha per year.

The project has shown that Mg is not lost from volcanic ash soils by leaching. Therefore, the cheapest Mg fertiliser can be used, even if it the most soluble.

The project has shown that K is not lost by leaching from alluvial clay soils. Therefore, future efforts to improve nutrient use efficiency, for example by fertiliser placement (being examined in the recently established Trial 517), are likely to have major economic impact.

Finally, CTP plantations (39% of plantation area in PNG) changed their fertiliser application practices as a result of research carried out in this project. Until 2005, that company spread fertiliser over the frond pile as it was believed that most feeder root activity was in that zone. After the results of our root activity distribution studies were presented to the industry in September 2005, the company changed to spreading fertiliser around the weeded circle. It is difficult to quantify the economic impact of the management change, but it is likely to be large, given the reduced losses of fertiliser.

9.3.2 Social impacts

Training of OPIC's extension staff in soil science and plant nutrition has led to a greater understanding, by smallholders, why good and balanced nutrition is important for highly productive palms. As production increases, there will be less demand to clear more land for oil palm, thus reducing the pressure on the resource and making it available for food gardens. This will decrease pressure on 'store-bought' food, thus increasing food security. As it is mainly the women who do the food gardens, an increased reliance on gardens will increase their standing in the family and community.

The social impacts of changed payment schemes and investments in oil palm productivity by smallholders has been examined in detail by the ACIAR projects that ran parallel to this one: ASEM/1999/084, 'Biophysical and socio-economic interactions of factors affecting productivity among oil palm smallholders in Hoskins and Popondetta' (1999-2002), and ASEM/2002/014 'Improving productivity and the participation of youth and women in the Papua New Guinea cocoa, coconut and oil palm industries' (2002-2007).

9.3.3 Environmental impacts

Improved management of Mg and K nutrition is expected to benefit the environment in two ways. Firstly, increased productivity and income from existing plantings has the potential to reduce pressure to clear nearby forest for food gardens or cash crops. Secondly, improved Mg and K nutrition will result in increased nitrogen-use efficiency, meaning less nitrogen entering the ground water and nearby streams. Movement of nitrogen into streams is probably the most important concern for off-site effects of production agriculture in this environment. Improved nitrogen-use efficiency also has the potential to reduce rates of soil acidification attributed to nitrate leaching.

9.4 Communication and dissemination activities

PNGOPRA Annual Reports

Project results were reported annually and distributed to PNGOPRA members (plantation companies and OPIC). The reports are also available on CD upon request:

- PNGOPRA Annual Research Report 2002
- PNGOPRA Annual Research Report 2003
- PNGOPRA Annual Research Report 2004
- PNGOPRA Annual Research Report 2005
- PNGOPRA Annual Research Report 2006
- PNGOPRA Annual Research Report 2007

PNGOPRA Scientific Advisory Committee meetings

Presentations by project team to PNGOPRA member organisations (plantation companies and OPIC):

- Poliamba, September 2001
- Mosa, September 2002
- Bialla, September 2003
- Lae, September 2004
- Port Moresby, September 2005
- Port Moresby, September 2006
- Port Moresby, September 2007

Workshops with OPIC extension staff

- Hoskins, WNBP, December 2004
- Poliamba, NIP, May 2005
- Hagita, MBP, July 2005
- Mosa, WNBP, November 2005
- Higaturu, OP, April 2006
- Mosa, WNBP, November 2006
- Higaturu, OP, January 2007
- Hagita, MBP, January 2007
- Poliamba, NIP, January 2007
- Bialla, WNBP, March 2007

PNG OPRA ‘Roadshows’

Presentations by PNGOPRA staff to plantation managers and OPIC extension officers:

- Milne Bay, February 2002

- Bialla, WNBP, August 2002
- New Ireland, August 2002
- Milne Bay 2002
- Oro Province, Feb 2003
- Hoskins, Sep 2003

PNGOPRA/OPIC Field Days

Numerous field days in all the smallholder areas have been conducted by PNGOPRA and OPIC staff throughout the life of the project. The field days involve many hundreds of smallholders, and OPIC and PNGOPRA staff explain research findings (Figure 47).

Other

Lecture to JCU MSc Students on oil palm agronomy

Presentation of PNG oil palm research to CSIRO Seminar series

OPRA-tive Word: Fertilising to reduce *Ganoderma* risk

OPRA-tive Word: Analysis of potassium in oil palm leaf and rachis samples: Is ‘double calcination’ required?

OPRA-tive Word: Improved fertiliser use on volcanic soils in Papua New Guinea

For scientific papers and conference presentations, see section 11.2.1.

Figure 47. Dancers (left) and PNGOPRA agronomist Jojo Papah talking to smallholders (right) at Ilimo Field Day, November 2002, Oro Province. Potassium and Mg deficiencies are common in the Ilimo area and smallholders in this area began applying K fertiliser during this project.

10 Conclusions and recommendations

10.1 Conclusions

Field trials on volcanic ash soils (WNB) with Mg (various sources) and K have shown no clear yield response to Mg or K, but the oldest trial is only 4 years since establishment, so responses may yet appear. Increasing supply of Mg decreases concentration of K in leaf tissue, and vice versa.

Mg and K are not lost from volcanic ash soils of WNB or alluvial soils of MBP and MP by leaching, due to the high CEC of the soils. Cation transport modelling was able to predict actual leaching profiles reasonably well, allowing extrapolation to different soil types and climate.

The WNB volcanic ash soils are relatively unweathered, consisting mostly of volcanic glass and feldspar, and their CEC is largely due to organic matter. The balance of cations is related to source of the ash and the degree of weathering: Exchangeable Ca dominates more as the soils weather.

Mg applied to volcanic ash soils is retained mostly in exchangeable form.

The alluvial soils of Morobe and Milne Bay provinces are dominated by smectite or vermiculite and have a high capacity to fix K: no K has moved below 80 cm depth after 13 years of MOP application.

Soil characteristics, such as CEC, cation adsorption, water retention and infiltration have been used to model cation movement through the soil. The model outputs closely reflect field measurements of cation movement and thus modelling will be a valuable tool for extending results to other situations.

Impacts of research are already apparent with the industry reassessing fertiliser applications. There has also been substantial training of industry personnel in aspects of soil science and plant nutrition.

10.2 Recommendations

10.2.1 Continuation of long-term field trials

The continuation of the field trials established in this project must now be assessed. The field trials represent an enormous investment and their results are critical for assessing economic benefits of Mg and K fertiliser applications. They were all established with an intended life of 10 years, to be maintained by PNGOPRA beyond the life of this ACIAR project. Ten years is considered necessary to properly assess the effects of treatments in this crop. However, many of the trials are on NBPOL plantations, and NBPOL has expressed an intention to discontinue support for PNGOPRA fertiliser trials by the end of 2009. Another factor in the consideration is that now we know that Mg is not lost from volcanic ash soils by leaching, the hypothetical basis of some of the trials has been disproved. We recommend that some of the trials on NBPOL plantations be discontinued to comply with their wishes, but we also recommend that some of those trials be continued (Table 16). Trial 146 is not of critical importance now that we know that low-solubility sources of Mg are not necessary on these soils. Trial 145 will be useful if the alternative sources of Mg are cost-competitive with kieserite on a cost/kg Mg (and there is a Mg response) and also if these Mg sources are to be considered as liming materials as well as Mg sources. Rapid rates of soil acidification came to light during the life of this project. Trial 146 is less important than T145, because the placement options investigated are not likely to be economic given that Mg is not lost by leaching. There is however the possibility that Mg uptake will be better with hotspot treatments due to the increased

Mg:Ca ratios established. T148 is valuable in that it assesses the response to Mg while avoiding the possible problems of small plots. It requires less input from PNGOPRA than the other trials as the yield recording is carried out by OPRS. It should therefore be continued, and the responsibility for applying fertiliser treatments perhaps transferred to NBPOL. Trial RM 03-1 is a basic factorial fertiliser trial, essential when a crop is being grown in an unfamiliar environment, so it should continue. RAI established the trial and has the resources to continue it. Trial 517 is the only activity underway to assess ways of improving K uptake efficiency and it should be continued.

Table 16. Recommendations for field trials established in this project

Trial	Year treatments commenced	Site owner	Recommendation
T144 KxMg response	2003	NBPOL	To continue, as knowledge of response is critical
T145 Mg sources	2004	NBPOL	To continue, as response to alternative Mg sources is required
T146 Mg sources and placement	2004	NBPOL	To continue as it may show benefit of ‘hotspots’ in relation to Ca competition with Mg
T148 Mg response, large plots	2003	NBPOL	To continue as it will provide information on genotype interactions
RM 03-1 NxKxPxS	2003	RAI (now owned by NBPOL)	To continue as this trial will provide guidance on N, P, K and S requirements. This trial would also be an opportunity to field-test the recommendations as set out in Webb (2008).
T517 K placement	2006	CTP	To continue as it is the only trial on K placement
T516 NxK	2008	CTP	To continue as it will provide information on NxK interactions in a young plantation
T504	1991	CTP	To continue as it will provide information on NxK interactions in an older plantation
T502b	-	CTP	Research plots maintained at replanting to investigate the residual effect of K build up.

10.2.2 Recommendations for managing Mg nutrition on volcanic ash soils of WNB

This project started with the hypothesis that Mg is rapidly lost form the root zone in this environment and that fertiliser management may need to change from surface application of soluble sources (kieserite) to alternatives. However, as it has been shown that Mg, even from soluble kieserite, is not being lost through leaching, the use of low solubility sources is not necessary; unless economically more viable.

Prior to this project it had not been possible to assess the economic benefit of applying Mg fertiliser, as there had been no response to kieserite in field trials. The Mg-response trials established in this project have been designed to overcome some potential problems with the previous trials, and they will provide definitive Mg-response information within their life (10 years, assuming they are continued). While these trials should be continued as suggested in Table 16, in light of the results obtained so far, it is time for the plantations to review their Mg usage in terms of economic returns.

Smallholder recommendations should follow those of the plantations, which can be achieved using the GIS approach established within the Agricultural Innovations Grants Facility project. Typically, smallholder blocks are matched to nearby plantation blocks based on soil type. The size weighted average for similar plantation blocks is then used as the recommendation for that smallholder.

10.2.3 Recommendations for managing K nutrition on alluvial soils of Milne Bay and Morobe

The inclusion of K in this project was instigated at the mid-term review. Thus, the trials are too young to provide data immediately useful to management at this stage. Thus it is recommended that all trials be continued. The fertiliser trials in MP will provide information on economic rates of N, K, P, and S that are directly useful to management. The NxK, and K placement trials in MBP will also provide information that is directly useful to management.

10.2.4 Recommendations for future research

Trial 502b should be continued until replanting. Following replanting, it is recommended that the research plots be maintained as they will provide information on the residual effect of K build up in the soil.

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11.2 List of publications produced by project

11.2.1 By the project team

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12 Appendixes

12.1 Appendix 1: Sampling site locations

ID in report	Province	Longitude	Latitude
Plantations and smallholder areas (approximate position of centre)			
Ambogo	OP	148.2370	-8.7183
Balaha	WNBP	151.0910	-5.2369
Bebere	WNBP	150.2500	-5.5928
Bialla	WNBP	151.0570	-5.3286
Bilomi	WNBP	150.6670	-5.6011
Buvussi	WNBP	150.3800	-5.6278
Dami	WNBP	150.3340	-5.5333
Garu	WNBP	150.0520	-5.5936
Haella	WNBP	149.9940	-5.5269
Hargy- see 'Bialla'			
Ilimo-Papaki	OP	147.9750	-8.9008
Kumbango	WNBP	150.2090	-5.6008
Luburua		151.2260	-2.8856
Maiwara	MBP	150.2730	-10.3325
Malilimi	WNBP	150.4390	-5.6628
Mamba	OP	147.6880	-8.8275
Navarai	WNBP	150.0200	-5.2569
Navo	WNBP	151.1670	-5.1139
Poliamba-see Luburua	NIP		
Ramu blk 409	MP	145.9250	-6.0131
Ramu blk 202	MP		
Sagarai	MBP	150.1940	-10.4308
Togulo	WNBP	150.1920	-5.6564
Waigani	MBP	150.2580	-10.3206
Walindi		150.0820	-5.4344
Field Trials (approximate position of centre)			
RM 1-03 (Ramu)	MP	145.9996	-6.0836
T129 (Kumbango)	WNBP	150.2156	-5.5911
T144 (Waisisi)	WNBP	150.4442	-5.4828
T145 (Walindi)	WNBP	150.0817	-5.4344
T146 (Kumbango)	WNBP	150.2019	-5.6167
T151 (Dami)	WNBP	150.3369	-5.5306
T502 (Waigani)	MBP	150.2586	-10.3208
T504 (Sagarai)	MBP	150.1942	-10.4314
Soil characterisation pits			
Ramu 1	MP	145.9996	-6.0836
Ramu 2	MP		
Ramu 3	MP		
Kumbango 1	WNBP	150.2019	-5.6167
Hargy 1	WNBP		
Poliamba 1	NIP	151.2260	-2.8856
Poliamba 2	NIP		
Waigani 1	MBP	150.2586	-10.3208
Sagarai 1	MBP	150.1942	-10.4314
Maiwara 1	MBP	150.2730	-10.3325
Maiwara 2	MBP		
Waisisi 2005	WNBP	150.4442	-5.4828
Waisisi 2006	WNBP		
Dami 2007	WNBP	150.3369	-5.5306
Gillman sample set			
See 'Plantations and smallholder areas' list			

For locations of the smallholder blocks sampled in West New Britain,
see Rogers et al (2006b)

Bialla

Subdivision	**VOP/LSS**	**Block**
MAMOTA	LSS	240-0881
MAMOTA	LSS	240-0879
MAMOTA	LSS	240-0964
MAMOTA	LSS	240-1009
MAMOTA	LSS	240-1032
MAMOTA	LSS	240-0939
MAMOTA	LSS	240-1050
MAMOTA	LSS	240-0990
MAMOTA	LSS	240-0977
MAMOTA	LSS	240-0978
MAMOTA	LSS	240-0988
MAMOTA	LSS	240-1018
MAMOTA	LSS	240-0967
MAMOTA	LSS	240-0933
MAMOTA	LSS	240-1037
MAMOTA	LSS	240-0975
SILANGA	LSS	242-0506
SILANGA	LSS	242-0442
SILANGA	LSS	242-0346
SILANGA	LSS	242-0423
SILANGA	LSS	242-0487
SILANGA	LSS	242-0503
SILANGA	LSS	242-0266
SILANGA	LSS	242-0300
SILANGA	LSS	242-0265
SILANGA	LSS	242-0288
SILANGA	LSS	242-0642
UASILAU	LSS	241-0154
UASILAU	LSS	241-0185
UASILAU	LSS	241-0205
LALOPO	LSS	246-1077
UMU	VOP	259-0001
UMU	VOP	259-0006
UMU	VOP	259-0010
UMU	VOP	259-0021
UMU	VOP	259-0027
GAEKEKE	VOP	260-0012
GAEKEKE	VOP	260-0009
GAEKEKE	VOP	260-0019
GAEKEKE	VOP	260-0013
KAI	VOP	255-0001
KAI	VOP	255-0012
UBAI	VOP	250-0042
UBAI	VOP	250-0059
SISIMI	VOP	256-0001
LAVEGI	VOP	251-0023
TIAURU	LSS	010-0292
TIAURU	LSS	010-0201
TIAURU	LSS	010-0336
TIAURU	LSS	010-0204
TIAURU	LSS	010-0230
TIAURU	LSS	010-0258
TIAURU	LSS	010-0211
TIAURU	LSS	010-0234
TIAURU	LSS	010-0340
WILELO	LSS	020-1116
WILELO	LSS	020-1109
WILELO	LSS	020-1177
WILELO	LSS	020-0609
WILELO	LSS	020-0803
WILELO	LSS	020-0802
WILELO	LSS	020-1171
WILELO	LSS	020-0687
WILELO	LSS	020-0734
WILELO	LSS	020-0789
WILELO	LSS	020-0855
WILELO	LSS	020-0749
WILELO	LSS	020-1184
BAREMA	LSS	030-1385
BAREMA	LSS	030-1393
BAREMA	LSS	030-1392
BAREMA	LSS	030-1395
BAREMA	LSS	030-1403
BAREMA	LSS	030-1370
BAREMA	LSS	030-1383
BAREMA	LSS	030-1374
MATILILIU	VOP	17-1716
MATILILIU	VOP	17-1702
MATILILIU	VOP	17-1722
MATILILIU	VOP	17-1752
MATAURURU	VOP	10-1008
MATAURURU	VOP	10-1024
EWASSE	VOP	35-0016
EWASSE	VOP	35-0024
KIAVA	VOP	11-1106
KIAVA	VOP	11-1127
SOI	LSS	31-1761
SOI	LSS	31-1739
SOI	LSS	31-6033
SOI	LSS	31-1772
SOI	LSS	31-1625
SOI	LSS	31-0619
SOI	LSS	31-1635
SOI	LSS	31-1752
SOI	LSS	31-1558
KABAIYA	LSS	33-2002
KABAIYA	LSS	33-1852
KABAIYA	LSS	33-1824
KABAIYA	LSS	33-1826
KABAIYA	LSS	33-1886
KABAIYA	LSS	33-1810
NOAU	VOP	07-001
NOAU	VOP	07-057
NOAU	VOP	07-043

Hoskins **Subdivision**	**Block**
Banuela	800757
Galewale	290004
Galilo	2700021
Gaungo	170020
Gaungo	170037
Gaungo	170115
Gaungo	170132
Karapi	400027
Koimumu	390010
Kololo	440007
Kapore	10263
Kapore	10268
Kapore	10318
Kapore	10332
Kapore	10371
Kwalakessi	130045
Kavutu	330008
Makasili	380004
Morokea	160065
Morokea	160074
Morokea	160144
Siki	90109
Siki	901064
Tamba	20414
Tamba	20469
Tamba	20555
Tamba	20573
Tamba	30579
Valoka	320008
Waisisi	230007

Oro

Subdivision	**Block**
Sorovi	121702
Sorovi	121730
Sorovi	131825
Sorovi	171034
Soputa	251069
Sorovi	280016
Waru(Igora)	510027
Waru(Igora)	520748
Waru(Igora)	520783
Girigirita(Igora)	540074
Girigirita(Igora)	540439
Ilimo	670008
Ilimo	670053
Ilimo	680001
Ombisusu	690043
Ombisusu	690063
Sorovi	830006
Arehe	AR-060217
Awowota	AW0-220068
Boru	B0-350002
Boru	B0-350059
Bapuhi	BAP-590022
Oitatande(Kipore?)	BLK-620193
Botue	BOT-389000
East Ambogo	EA-030301
Embi	EMBI-800082
Girigirita	GIR-540302
Hujava	HUJ-420019
Iora(Kokoda)	I0-680375
Igora	IG-080080
Igora	IG-080093
Igora	IG-101159
Igora	IG-101190
Igora	IG-101235
Igora	IG-101263
Igora	IG-101278
Igora	IG-111403
Igora	IG-111452
Igora	IG-111466
Igora	IG-111471
Igora	IG-111502
Igora	IG-111519
Igora	IG-111550
Igora	IG-111560
Igora	IG-111599
Igora	IG-530005
Ilimo	IL-6700024
Ilimo	ILI-670141
Iora(Kokoda)	IOR-680384
Koropata	K0-310838
Kokoda	K0-680172
Kokoda	K0-680178
Kanari(Igora)	KA-540146
Kokoda	KAD-680091
Kakandeta	KAK-280008
Kausada	KAU-660002
Kumusi	KU-630010
Oitatande	OIT-620056
Oitatande	OIT-620066
Oitatande	OIT-620118
Papoga	PAP-640034
Papoga	PAP-640036
Papoga	PAP-640084
Pirive(Kokoda)	PI-670118
Sakita	SAK-750046
Soputa	SOP-251069
Sorovi	SOR-040251
Sorovi	SOR-121
Sorovi	SOR-121653
Sorovi	SOR-121658
Sorovi	SOR-121674
Sorovi	SOR-121697
Sorovi	SOR-121716
Sorovi	SOR-121739
Sorovi	SOR-121762
Sorovi	SOR-121782
Sorovi	SOR-121788
Sorovi	SOR-121793
Sorovi	SOR-121797
Sorovi	SOR-121810
Sorovi	SOR-170006
Sorovi	SOR-171034
Sorovi	SOR-180002
Sorovi	SOR-610001
Timbeki	TIM-340038
Timbeki	TIM-340042
Timbeki	TIM-340043
Tunana	TUN-710112
Urio	URI0-800125
Waru(Waseta?)	WA-300028
Waru(Waseta?)	WA-310010
Waru(Waseta?)	WA-310104
Wana(Ilimo)	WAN-670067

12.2 Appendix 2: Soil chemical properties (pit sample set)

Site	Depth	pH_w	pH_{CaCl2}	EC	CEC	Exch Ca	Exch Mg	Exch K	Exch Na	ECEC	OC	N	Available P
	(cm)			(dS/m)	(cmol+/kg)						(%)	(%)	(mg/kg)
Bialla	0		6.01		9.64	10.98	0.56	0.17	0.15				
	35		5.95		4.70	4.27	0.35	0.06	0.14				
	45		5.96		1.79	1.28	0.17	0.05	0.08				
Dami - meaned control plot data	0	6.04	5.61	0.12		10.60	1.73	0.30	0.08				
	15	6.13	5.67	0.08		8.18	1.11	0.16	0.12				
	40	6.44	5.76	0.02		1.61	0.19	0.19	0.18				
	80	6.63	5.86	0.01		1.04	0.12	0.18	0.13				
	100												
	110	6.76	5.91	0.01		1.25	0.09	0.19	0.10				
Dami - pit	0-5cm				9.52	10.70	1.41	0.13	0.20				
	15-20cm				4.31	4.24	0.41	0.08	0.24				
	40-45cm				1.65	1.26	0.11	0.29	0.36				
	80-85cm				0.99	0.88	0.09	0.25	0.20				
	110-115cm				1.00	0.67	0.07	0.27	0.17				
Kumbango	0		4.89		5.37	4.36	0.61	0.57	0.21				
	25		5.34		1.97	1.69	0.19	0.45	0.23				
	75		5.51		16.91	14.97	2.53	1.06	0.61				
Maiwara - 1&2 meaned data	0	5.9	5.41	0.097	52.07	31.57	17.22	0.8	0.78		4.63		71.17
	31	6.21	5.53	0.054	48.46	27.09	21.09	0.11	0.92		1.02		1.77
	65	6.7	6.13	0.056	55.92	21.61	21.61	0.09	1.18		0.4		3.4
	0 - HP												
	0 - WC												
Navo	0	6.21	5.49	0.06	3.32	3.76	0.56	0.02					
	1	6.32	5.64	0.06	5.11	5.50	0.87	0.03					
	5	6.51	5.74	0.05	3.60	4.29	0.65	0.03					
	15	6.74	5.85	0.03	2.21	2.31	0.39	0.03					
	30	7.04	6.09	0.01	1.17	1.07	0.24	0.03					
	50	7.15	6.16	0.01	1.02	0.90	0.23	0.03					
	70	7.14	6.18	0.01	1.27	1.05	0.28	0.04					
	90	7.11	6.17	0.02	2.10	1.81	0.42	0.05					
	110	7.16	6.14	0.01	2.32	2.09	0.52	0.06					
	130	7.22	6.13	0.01		1.86	0.52	0.08					
Poliamba - 1	0		4.66		6.63	6.96	0.62	0.35	0.08				
	40		4.47		5.11	1.25	0.18	0.05	0.14				
Ramu - 1	0				49.34	37.53	16.95	5.15	0.51				
	40				70.72	52.19	21.22	0.66	1.42				
Ramu - 2 (409)	0		5.61		55.71	45.18	19.21	2.61	0.35				
	15		5.72		62.95	42.48	22.31	0.92	0.40				
	75		5.80		65.1	38.84	23.25	0.14	0.59				
	105												
Ramu - 3 (202)	0		5.86		55.06	38.20	16.41	4.47	0.40				
	20		5.89		52.74	35.61	12.59	2.74	0.51				
	40		5.90		58.86	35.60	11.43	2.84	0.95				
Sagarai	0		5.92		40.27	35.52	8.61	0.12	0.34				
	15		5.95		42.49	30.63	14.75	0.12	0.32				
	35		5.99		45.83	28.41	16.25	0.03	0.28				
	85		6.03		42.75	27.76	18.53	0.04	0.35				
	0 - BZ												
	0 - WC												
	0 - FT												
	0 - FP												
Waigani	0		4.68		42.18	31.38	13.32	0.24	0.66				
	17		5.91		53.89	41.18	20.83	0.03	0.80				
	50		6.37		50.79	39.81	21.55	0.02	0.83				
	90		6.36		51.23	38.45	20.38	0.03	0.66				
	0 - BZ				35.39	25.45	11.00	0.11	0.61				
	0 - WC				36.23	30.83	13.74	0.13	0.63				
	0 - FT				38.99	27.50	12.74	0.12	0.65				
	0 - FP				41.17	20.62	11.42	0.11	0.68				
Waisisi - 2005	0												
	10												
	18												
	30												
	50												
Waisisi - 2006	0		5.91		13.57	15.03	1.12	0.10	0.23				
	16		5.95		1.87	1.65	0.16	0.06	0.16				
	45		5.92		1.49	1.40	0.15	0.04	0.11				
	67		5.94		0.82	0.68	0.09	0.10	0.15				
Walindi	0-1cm	4.92	4.36	0.08		5.060	1.36	1.129					
	1-5cm	5.05	4.34	0.03		4.544	1.45	0.957					
	5-10cm	5.23	4.50	0.02		5.272	1.53	0.980					
	10-20cm	5.54	4.76	0.02		5.913	1.53	1.278					
	20-40cm	5.97	5.06	0.02		8.064	1.79	1.453					
	40-70cm	6.24	5.29	0.02		9.642	1.75	0.834					

12.3 Appendix 3: Soil hydraulic and solute retention parameters

Site	Depth (cm)	Bulk Density (g/cm^3)	Infiltration Rate (cm/hr)	Hydraulic Properties - van Genuchten				Freundlich Langmuir - Mg			Freundlich Langmuir - K		
				θs (cm^3/cm^3)	θr (cm^3/cm^3)	α (/cm)	η	Kd (mEq/L)	η (mEq/L)	β	Kd (mEq/L)	η (mEq/L)	β
Bialla	0	0.69	74	0.68	0.31	0.018	1.75	26.6	0.276	0.702	4.4	0.046	0.771
	35	0.81	26	0.70	0.40	0.018	1.46	37.2	0.791	0.681	5.2	0.110	0.619
	45	1.20	31	0.51	0.23	0.021	1.39	15.5	0.866	0.701	3.1	0.173	0.863
Dami	0	0.85	66	0.78	0.25	0.035	1.50	40.2	0.316	0.437			
	15	0.75		0.64	0.17	0.020	2.08	16.5	0.173	0.448			
	40	0.88	150	0.54	0.07	0.044	1.86	7.7	0.355	0.542			
	80	0.82		0.56	0.05	0.033	1.84	6.0	0.410	0.500			
	100		64										
	110	0.99		0.51	0.05	0.026	1.96	4.6	0.370	0.448			
Kumbango	0	0.79	4	0.69	0.28	0.015	1.60	17.1	0.318	0.522			
	25	0.98	42	0.54	0.11	0.023	1.73	8.5	0.331	0.496			
	75	1.32	22	0.61	0.16	0.024	1.52	46.8	0.277	0.669			
Maiwara - 1	0	0.68	241	0.76	0.34	0.008	1.69						
	31	0.98	129	0.68	0.42	0.004	1.70						
	65	1.03	153	0.66	0.38	0.006	1.78						
	0 - HP		47										
	0 - WC		454								10.0	0.020	1.224
	0 -FT										15.0	0.027	0.937
Maiwara - 2	0	0.81	27	0.70	0.35	0.007	1.80						
	31	1.01	85	0.68	0.44	0.003	1.83						
	65	1.03	152	0.66	0.39	0.006	2.01						
	0 - HP		83										
	0 - WC		1136										
Navo	0	0.86	282	0.50	0.09	0.063	1.54	18.8	0.565	0.544	1.7	0.051	0.806
	1							28.4	0.555	0.572	2.3	0.045	0.552
	5							28.2	0.782	0.613	3.1	0.086	0.646
	15							24.7	1.116	0.708	2.6	0.117	0.635
	30							22.2	1.901	0.765	1.4	0.122	0.300
	50	0.93	345	0.51	0.14	0.065	1.63	15.4	1.510	0.610	1.2	0.115	0.337
	70							27.2	2.138	0.797	2.6	0.205	0.929
	90	0.74	121	0.63	0.23	0.075	1.54	28.2	1.346	0.688	3.0	0.144	0.882
	110							33.5	1.442	0.648	4.4	0.189	0.704
	130	0.98	28	0.55	0.20	0.019	1.83	34.5	1.487	0.648	5.2	0.224	0.609
Poliamba - 1	0	0.83	53	0.59	0.38	0.080	1.52	33.5	0.418	0.722	11.6	0.145	0.809
	40	0.97	1	0.59	0.51	0.075	1.35	72.0	0.799	0.804	4.1	0.079	1.792
Ramu - 1	0	1.36	144	0.60	0.36	0.048	1.51						
	40	0.96	3	0.55	0.37	0.024	1.68						
Ramu - 2	0	0.87	169	0.60	0.41	0.030	1.55				30.3	0.045	0.296
	15	1.05	29	0.66	0.46	0.025	1.46				41.1	0.062	0.582
	75	1.21	3	0.63	0.47	0.033	1.54				50.4	0.080	0.555
	105		59										
Ramu - 3	0	0.90	131	0.61	0.39	0.028	1.58				61.1	0.103	0.428
	20	1.34	22	0.53	0.39	0.029	1.91				44.2	0.086	0.586
	40	1.33	25	0.48	0.26	0.039	1.85				53.2	0.105	0.642
Sagarai	0	0.89	17	0.68	0.42	0.009	1.66				19.0	0.043	0.671
	15	1.00	17	0.63	0.43	0.013	1.56				20.1	0.044	0.731
	35	1.13	100	0.58	0.44	0.015	1.58				18.8	0.042	0.781
	85	1.12	33	0.59	0.44	0.019	1.55				12.9	0.028	0.850
	0 - BZ												
	0 - WC										33.8	0.061	0.464
	0 - FT												
	0 - FP												
Waigani	0	0.87	81	0.65	0.38	0.013	1.57				22.0	0.057	0.757
	17	1.05	27	0.63	0.44	0.007	1.68				25.9	0.042	0.657
	50	1.14	38	0.62	0.47	0.011	1.83				33.4	0.054	0.662
	90	1.13	27	0.62	0.42	0.013	1.64				29.2	0.063	0.781
	0 - BZ										15.7	0.043	0.655
	0 - WC										28.5	0.079	0.588
	0 - FT										23.7	0.066	0.656
	0 - FP										20.8	0.058	0.701
Waisisi - 2005	0	0.76	87	0.66	0.12	0.013	1.49						
	10	0.85	87	0.52	0.11	0.013	2.18						
	18	0.85	13	0.54	0.09	0.015	1.69						
	30	0.61	94	0.62	0.07	0.042	1.52						
	50	0.55	736	0.66	0.10	0.018	1.76						
Waisisi - 2006	0	0.68	87	0.64	0.17	0.020	2.08	38.9	0.231	0.443	5.5	0.031	0.733
	16	0.71	13	0.51	0.06	0.023	1.81	10.3	0.511	0.464	5.0	0.241	0.477
	45	0.93	94	0.57	0.08	0.030	1.54	11.5	0.640	0.538	3.6	0.200	0.668
	67	0.70	736	0.54	0.05	0.053	1.61	7.9	0.835	0.503	4.0	0.450	0.397