Limited movement of fertiliser-derived Mg and K through volcanic ash and alluvial clay soils of Papua New Guinea

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Abstract
Crop symptoms of K and Mg deficiency are common on the coastal plains of Papua New Guinea. It was hypothesised that fertiliser uptake efficiency in oil palm is limited in these environments due to leaching loss resulting from high rainfall and high soil exchangeable Ca contents. Two field experiments were carried out on volcanic ash soils to determine the effect of fertiliser type ($MgSO_4$, MgO or $MgCO_3$) on movement of Mg. In one trial the fertilisers were applied to 36-palm plots over a period of 3 years before soil sampling. In the other trial the fertilisers were applied evenly over 4 m^2 plots and the soil was sampled after 42 days and 1 year. A third field experiment, in which various rates of K fertiliser had been applied to an alluvial clay soil over a period of 13 years (36-palm plots), was sampled to determine the depth to which K had moved. Concentration profiles and mass balances showed that neither Mg nor K moved deeper than 0.6 m depth in any of the trials. In the K trial, approximately half of the fertiliser-derived K was fixed in non-exchangeable form. Results suggest that loss of K or Mg by leaching is not of concern in these environments.

Key Words
Exchangeable cations, K fixation, kieserite, magnesium carbonate, magnesium oxide, oil palm

Introduction
On the coastal plains of Papua New Guinea, symptoms of both K and Mg deficiencies occur across a range of crop species. Symptoms of both K and Mg deficiencies are widespread in areas of West New Britain and Oro Provinces with recent volcanic ash soils, whereas symptoms of K deficiency are common on alluvial clays of Milne Bay Province and clay soils on raised coral in New Ireland Province (Bleeker 1983). In the areas with K deficiency symptoms, crop responses to muriate of potash (KCl, hereafter referred to as MOP) are generally large, but the proportion of applied K actually taken up (uptake efficiency), is generally unknown. In the case of Mg, responses to kieserite ($MgSO_4.H_2O$) have been rare on volcanic ash soils, despite the presence of symptoms consistent with deficiency, and good responses in Mg-deficient crops elsewhere (Turner 1981). The deficiencies of K, and possibly also Mg, are presumably largely due to the high ratios of exchangeable Ca:K and Ca:Mg in all those soils (Bleeker 1983) rather than low cation exchange capacity (CEC). In addition, high ratios of Mg:K may contribute to K deficiencies in the alluvial clay soils. Because of the high rainfall and high content and generation of exchangeable Ca from rapidly weathering minerals in these soils, it was thought that K and Mg applied as soluble fertilisers might rapidly leach out of the root zone, leading to low uptake efficiency of K and lack of response to soluble Mg fertiliser. In this work we set out to measure a) the amount of leaching loss of Mg from a volcanic ash soil of West New Britain to which kieserite or less soluble forms of Mg fertiliser had been applied, and b) the fate of fertiliser-applied K in a long-term fertiliser trial in oil palm on alluvial clay in Milne Bay.

Methods
Trial 502: K fertiliser trial on alluvial clay in Milne Bay
The fate of fertiliser-applied K was measured in Trial 502. The area has an annual average rainfall of approximately 2,200 mm, and the well-structured smectitic clay soils have high CEC (35-47 cmol+/kg throughout top 1 m), dominated by Ca (20-32 cmol+/kg) and Mg (11-18 cmol+/kg). The trial is a complete factorial design, with sulphate of ammonia (SOA) applied at 0, 2, 4 or 6 kg/(palm.year), MOP applied at 0, 2.5, 5.0 or 7.5 kg/(palm.year), triple superphosphate applied at 0 or 2 kg/(palm.year), and empty fruit bunches (EFB) at 0 or 300 kg/(palm.year). The soil surface of the plantation can be classified into surface management zones (Figure 1). Fertiliser is applied by hand, with some zones, usually the BZ and FP zones, receiving more than others. Palms had been planted in 1986 at a density of 127 palms/ha, treatments commenced in 1995, and soils were sampled in 2005-2006. Soil samples were taken from plots that had received MOP at zero or 7.5 kg/(palm.year) and the highest rate of SOA. Auger samples were taken in a grid pattern covering the 4 palm units (Figure 1) in the centre of each plot (12 holes in WC, 7 in FPa, 5 in FPb

and 39 in BZ) to a depth of 1.4 m at depth increments of 0.2 m, and combined for each depth, zone and plot combination. Care was taken to prevent mixing of soil from different depths.

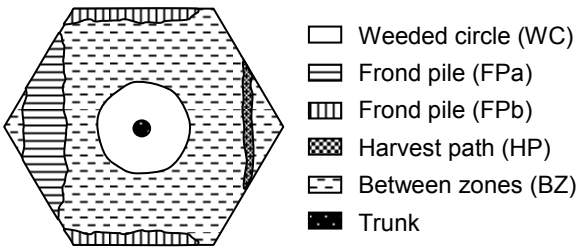

Figure 1. Surface management zones in the fertiliser trials. The hexagon, whose perimeter is defined by the midpoint between adjacent palms, is a 'palm unit', the repeating unit in oil palm plantations. The width of the palm unit, which equals the distance between palm centres, is approximately 9.0 to 9.8 m (at spacings of 143 and 120 palms/ha, respectively).

Trial 145: Mg fertiliser trial on volcanic ash soil at Walindi, West New Britain
Kieserite ($MgSO_4.H_2O$) is the most commonly used form of Mg fertiliser, but as there were concerns about its solubility and possible loss by leaching, Trial 145 was established to compare different forms of Mg fertiliser. The site has approximately 3,900 mm annual rainfall and clayey volcanic ash soil, with the soil (0-0.2 m depth, mean of all 48 plots) having pre-treatment pH_{water} of 5.7 and effective CEC of 11.2 cmol+/kg, comprised of 7.1, 1.5, 1.9, 0.2 and 0.5 cmol+/kg exchangeable Ca, Mg, K, Na and acidity, respectively. Anion exchange capacity was not measured, but at similar sites it has been measured at <0.1 cmol-/kg at soil pH. The treatments were application of kieserite, $MgCO_3$, MgO, and a $MgCO_3$-MgO mix at rates supplying Mg at 0, 0.34 or 0.68 kg/(palm.year). All plots received basal applications of N, and occasionally K and B fertiliser. Palms had been planted in 1999 at a density of 120 palms/ha, treatments commenced in 2004, and soils were sampled in 2007. Sampling was in the zone of fertiliser application, at depth increments of 0-0.01, 0.01-0.05, 0.05-0.1, 0.1-0.2, 0.2-0.4 and 0.4-0.7 m. The samples from 0-0.2 m were taken using a trowel and spade and the deeper ones were taken with an auger.

Trial 151: Mg leaching trial on volcanic ash soil at Dami, West New Britain
When sampling Trial 145 to determine the fate of added Mg, it was unclear exactly where the fertiliser had been applied and where to sample. Therefore, Trial 151 was established in a young plantation on a sandy volcanic ash soil in order to quantify Mg movement. The soil (0-0.1 m depth, mean of control plots) had pH_{water} of 6.2 and effective CEC of 12.8 cmol+/kg, comprised of 10.6, 1.8, 0.3 and 0.1 cmol+/kg exchangeable Ca, Mg, K and Na, respectively. Anion exchange capacity was negligible at soil pH. Mg fertilisers (same ones as in Trial 145) were spread evenly over the soil surface in 2x2 m plots (4 replicates) at rates supplying Mg at 0 or 56.5 g/m^2. That application rate was chosen as it approximates the rate applied to the fertilised zone in commercial practice. The plots were sampled down to 1.5 m (auger holes in central 1 m^2) when cumulative rainfall reached 745 mm (after 42 days) and 2,500 mm (after 1 year).

Soil analyses and solute transport modelling
Soil samples from all trials were analysed for exchangeable cations by compulsive exchange (Gillman and Sumpter 1986). In Trial 502, additional analyses were: non-exchangeable plus exchangeable K using tetraphenyl borate (TPB) extraction (Cox *et al.* 1996); and bulk density in selected samples. In Trial 151, additional analyses were; sulphate-S throughout the profile; forms of Mg in the 0-0.1 m depth layer, measured by sequential extraction (Uzo and Melsted 1972) and X-ray fluorescence (total Mg); bulk density; saturated hydraulic conductivity; water retention curves; and adsorption isotherms for K and Mg. The latter three analyses were carried out in order to facilitate solute transport modelling using HYDRUS-1D (Simunek *et al*. 1998).

Results

K movement through alluvial clay soil (Trial 502)
Of the K that had been applied in the previous 13 years and remained in the soil, most was in the top 0.2 m, and none was detected below 0.6 m (Figure 2). In the K-fertilised soil, TPB-K content was about double that of exchangeable K and followed a very similar pattern with depth. This means that the amount of non-exchangeable K was approximately equal to the amount of exchangeable K. By contrast, the ratio of non-exchangeable K to exchangeable K was much higher in the soils that received no K fertiliser (data not shown). The amount of fertiliser-applied K in the soil was calculated by subtracting the mean amount of TPB-K in the plots with no MOP applied from that in the plots that had had MOP applied. The total amount of fertiliser-applied K in the soil was 3,564 kg/ha. The amount of K sequestered and exported can also be

calculated from trial data or other estimates. The amount of K in standing biomass at the time of sampling was estimated at 808 kg/ha, and the amount estimated to have been exported in fruit bunches over the course of the trial was 1,690 kg/ha. This comes to a sum of 6,062 kg/ha, which is remarkably close to the amount of fertiliser that had been applied (6,191 kg/ha). Therefore, there appears to have been no significant loss of K from the site in runoff or leaching. Presumably most of this K will be available for uptake, although K in non-exchangeable form is only likely to become available if exchangeable concentrations drop sufficiently.

Mg movement through volcanic ash soils (Trials 145 and 151)

In Trial 145, Mg from the least soluble sources ($MgCO_3$, MgO, and $MgCO_3$/MgO) remained in high concentrations near the surface (Figure 3). Indeed some lumps of MgO were still visible on the surface after 3 years. But surprisingly, exchangeable Mg concentrations were high in the top 0.01 m even where Mg had been supplied as soluble kieserite. In fact, it appears that no Mg had moved more than 0.2 m downwards in any of the treatments. Results were similar in the sandy soil of Trial 151; fertiliser-derived Mg was not detected below 0.2 m (Figure 4). By contrast, all of the sulphate applied in the kieserite treatment had moved out of the surface layer, and sulphate concentration increased with depth (Figure 5). While it was clear that the applied Mg was retained in the surface soil layers, exchangeable Mg did not account for all the Mg applied. Total Mg content of the control soil was 6,894 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. Most of the fertiliser-derived Mg ended up in the exchangeable fraction; 63, 74 and 63% of that applied as kieserite, MgO and $MgCO_3$, respectively. In the kieserite and MgO 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 $MgCO_3$ 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. Results presented here are for the sampling at 42 days, but Mg had not moved significantly deeper after 1 year. Solute transport modelling using HYDRUS-1D satisfactorily simulated the movement of kieserite-derived Mg through the profile (Figure 4).

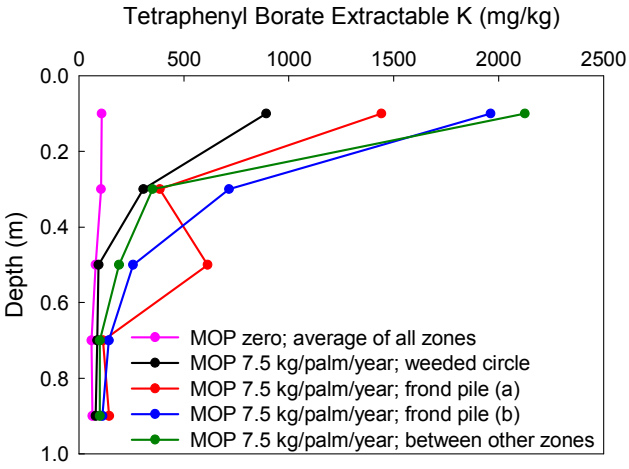

Figure 2. Tetraphenyl borate extractable K content of soil in plots to which MOP had been applied or not over 13 years (Trial 502). Values are means of 4 replicate plots.

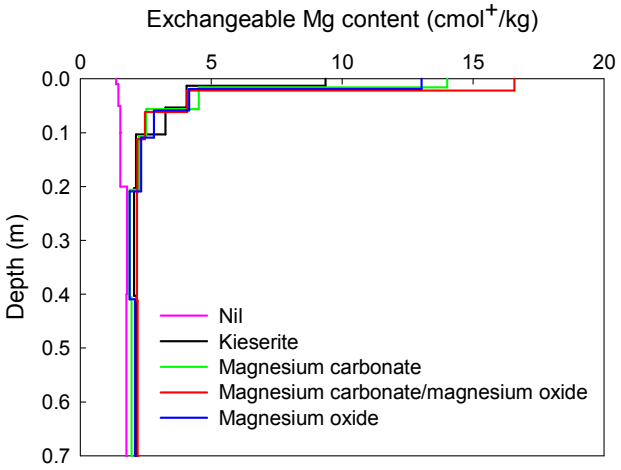

Figure 3. Distribution of exchangeable Mg with depth in the zone of fertiliser application in plots to which various forms of Mg fertiliser had been applied or not over 3 years (Trial 145). Values are means of 4 replicate plots. Concentrations in the +Mg treatments are 'normalised' so that the total amount of Mg in the profiles equals the average amount in all +Mg plots. This was done to obtain a comparative picture of distribution with depth, removing variability in actual values due to uneven distribution of fertiliser.

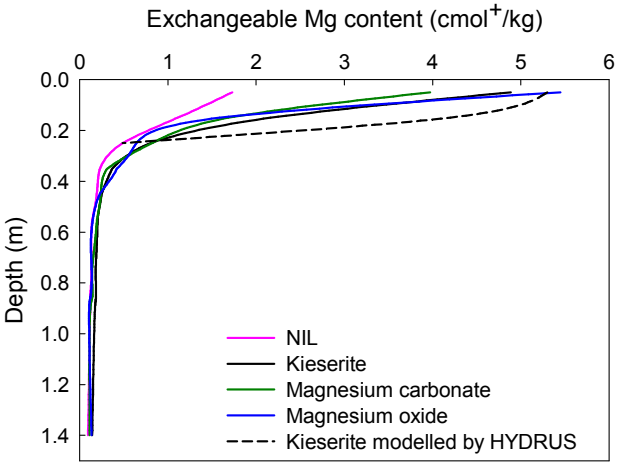

Figure 4. Exchangeable Mg content of plots to which one application of Mg fertiliser (various forms) had been made 42 days (and 745 mm rainfall) earlier (Trial 151). The dashed line shows concentration modelled using HYDRUS-1D.

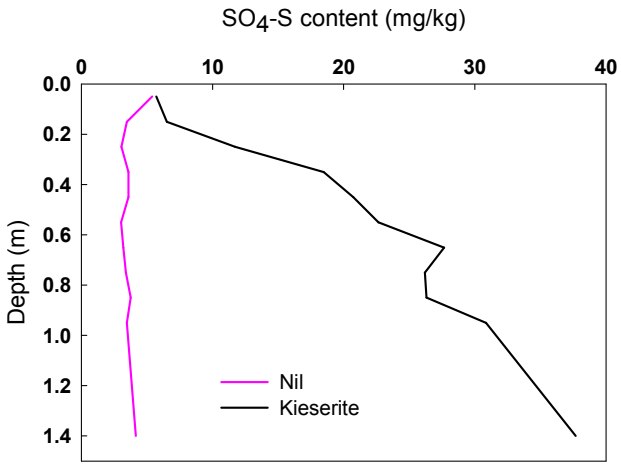

Figure 5. Concentration of sulphate-S in plots to which kieserite had been added or not 42 days (and 745 mm rainfall) earlier (Trial 151).

Conclusion

Despite high rainfall and high exchangeable Ca contents, fertiliser-applied Mg and K did not move below the top 0.6 m of the soils examined. The soils had sufficient CEC to retain all the applied Mg and K, even the sandy volcanic ash soil examined. In the volcanic ash soil, most of the fertiliser-derived Mg was retained in exchangeable form. In the alluvial clay, approximately half of the fertiliser-derived K retained in the soil was fixed into non-exchangeable forms. Leaching loss of K or Mg is therefore not of concern on these soils.

Acknowledgments

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