VG039

Vegetable production & water pollution on the Western Australian coastal plain

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VG039

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Final report of investigation into the use of gypsum-amended red mud as a soil-amendment on horticultural properties on the swan coastal plain.

W. J. Robertson, I. R. McPharlin and R.C. Jeffery

From project : Vegetable Production and Water Pollution on the Swan Coastal Plain (Project No. V/0039/RO)
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Recommendations

The recommendation from this research is that red mud/gypsum (RMG) not be recommended for widespread commercial use on vegetable crops because of the detrimental effects of freshly-applied RMG on the yield of two vegetable crops commonly grown on the Swan Coastal Plain, namely potatoes and cauliflowers. It is also felt that the costs associated with RMG application and the increased fertiliser inputs required on freshly-applied RMG outweigh the potential benefits, both in terms of reduced P leaching into the environment and of increased plant available P for use in soil-testing. However, RMG which has been applied to sites for several years and is highly leached may not have these detrimental effects and needs to be investigated.

Industry summary.

Amending pale sandy soils with 120 t red mud/ha (freshly-applied) increased the amount of fertiliser P held in the top 15 cm of soil, although the corresponding soil-test P levels at the beginning of the following crop were small, being only 5 to 10 ppm greater than on unamended soil. This is not sufficient soil-test P to allow soil-testing to be used effectively for the management of crops on amended soil, based on soil-test requirements on yellow Karrakatta sands. Another problem for soil-testing on red mud-amended soils in the short term is that the red mud cannot be mixed into the soil properly using field equipment, so that the soil-test measurement on a sample of soil is likely to be very variable. However, mixing may improve over time through repeated hoeing and the action of plant roots and water in breaking down aggregates of RMG.

The availability of P to plants was reduced on amended soil for all crops tested (carrots, onions, Chinese cabbages, cabbages, lettuce, cauliflowers and potatoes) on freshly-applied RMG. The yield of potatoes and cauliflowers was also reduced on amended soil for reasons not related to P availability.

Consequently, the costs associated with red mud application and with increased initial fertiliser applications appear to exceed the benefits in the short term, both from the point of view of preventing environmental degradation and of improving commercial management practices.

However, no results were obtained on red mud which had been on a site for several years, so the effects of old and highly leached red mud are not known.

Technical summary.

Amendment of poor sandy soils on four sites with 120 t RMG/ha (freshly-applied) increased the Phosphorus Retention Index (PRI*) of the top 15 cm of soil by 3 to 4 units. This was sufficient to significantly increase P retention in the top 15 cm of soil on two sites, although high variation means that this increase cannot be quantified accurately. Residual bicarbonate-extractable P only increased by between 5 and 10 ug/g between 0 and 60 or 0 and 90 t RMG/ha, when approximately 200 kg P/ha was applied. Further investigation is needed into the nature of soil reactions between RMG and applied P and also the relationship between bicarbonate-extractable P and plant available P in RMG-amended soil, before soil-testing can be used as a management option on amended soils. The pH of the soil (measured in water) increased by 1 to 2 units between 0 and 120 t RMG/ha. The long term effects of RMG on soil pH are not known.

Red mud/gypsum reduced the availability of P to all plants grown on amended soil (carrots, onions, Chinese cabbage, cabbage, lettuce, cauliflowers and potatoes), thereby increasing the level of currently applied P necessary to achieve 99 % of maximum yield and decreasing economic return (except in the case of lettuce, where greater moisture content increased fresh weight yields by 15 t/ha between 0 and 60 t RMG/ha). Maximum yields of potatoes and cauliflowers were reduced by 23 % and 25 % respectively between 0 and 120 t RMG/ha, although the reason is unclear. The reduction in cauliflower yields on residual P meant that no conclusion could be reached as to the residual effect of P on RMG-amended soil, although this is expected to be small given the small increase in residual bicarbonate-extractable P.

No health risks were identified from heavy metal contents and radiation doses from produce grown on amended soil, although a greater range of crops needs to be assessed. A long term reduction in soil pH may increase the availability of heavy metals such as lead, cadmium, nickel, cobalt and mercury.

All results obtained in this project were based on freshly-applied RMG or RMG which had only been applied for 1 to 2 years. It is not known how old and highly leached RMG (i.e. 5 to 10 years old) will affect P retention or plant growth.

Introduction

Intensive animal and plant industries on the coarse sandy soils of the Swan Coastal Plain have been implicated as one of the contributors to the nitrogen and phosphorus (P) pollution of ground and surface water bodies (lakes, rivers, estuaries) on the coastal plain (Cargeeg *et al.* 1988; Kinhill Engineers 1988). One of the major problems resulting from this pollution is algal growth in surface water bodies. As algae are able to fix atmospheric nitrogen, it is the level of P in the water which determines the amount of algal growth, under most conditions (McComb *et al.* 1984).

The ability of soils to sorb applied P depends largely on their iron and aluminium (sesquioxides) contents (Allen *et al.* 1991, Matar *et al.* 1992). Horticulture was first developed on the coloured sands of the Cottesloe and Karrakatta Associations (McArthur and Bettenay 1960). These soils have relatively good P retention so that almost all of the P applied over several years of cultivation will remain in the top 1m of soil (McPharlin *et al.* 1990). The strategy for managing P applications on these soils is to use soil-testing to minimise fertiliser inputs. Soil-testing requires that the soil is capable of holding sufficient plant-available P ('superbank') at the planting of the crop to allow the crop to reach maximum yield. Cottesloe and Karrakatta sands were observed to have more than adequate plant-available P in the surface soil (McPharlin *et al.* 1990) for the maximum yield of carrots (McPharlin *et al.* 1994b) and cauliflowers (McPharlin *et al.* unpublished data).

However, urban development is forcing horticulture onto the grey sands of the Bassendean Association (McArthur and Bettenay 1960). These soils have very low sesquioxide contents. As a result, they have a very low capacity to sorb applied P. These soils leach more P into the ground water than do Cottesloe and Karrakatta sands (Kinhill Engineers 1988). They are also unable to hold enough plant available P to allow crops to reach maximum yield (McPharlin *et al.* 1990).

The fines (< 150 μm diameter) of the by-product from aluminium extraction is called red mud. It contains large amounts of sesquioxides and strongly sorbs P (Barrow 1982; McPharlin *et al.* 1990). Barrow (1982) suggested that it can be applied to the grey sands of the Swan Coastal Plain in order to increase the P sorption of these soils. However, red mud is alkaline because it contains soluble sodium carbonate and bicarbonate. This alkalinity needs to be neutralised before the red mud can be applied to horticultural soils. Gypsum is commonly used for this purpose. It causes the precipitation of calcium carbonate, which buffers the red mud at a pH of 8.5 to 9 (Barrow 1982).

Red mud (both with and without added gypsum) has been observed to significantly reduce the amount of P leached from grey sands (Ho 1989; Vlahos *et al.* 1989). Ward

(1983) tested rates of red mud/gypsum (RMG) up to 1680 t/ha but Vlahos *et al.* (1989) observed that the amount of P leached from a grey sand of the Bassendean Association at 4000 t RMG/ha was the same as at 500 t RMG/ha. No previous work has been done on the effect of RMG on the 'superbank' of grey sands, although preliminary work shows that 256 t RMG/ha increased the Phosphorus Retention Index (PRI) of a grey sand from approximately zero to 7.6 units (McPharlin *et al.* 1994azx). This is a similar PRI to that of a virgin Cottesloe sand. Consequently, RMG at these levels would be expected to increase the plant-available P in the soil to a level similar to that observed in Cottesloe sands, thus allowing the use of soil-testing to manage P inputs.

Ward (1983) tested the effect of RMG application on the concentrations of a range of heavy metals in medics and sub-clover and did not observe any significant increases with level of RMG. However, the uptake of heavy metals varies between plant types (Mitchell *et al.* 1978), so the concentrations of heavy metals in vegetables must also be tested to ensure that there are no adverse health effects of using RMG. Radiation also needs to be tested as the red mud is mined from soil where the background radiation is several times higher than that on the coastal plain (Toussaint 1988).

The aim of this project was to assess the potential of RMG at moderately low rates for use as a soil amendment on grey sands used for vegetable production on the Swan Coastal Plain. Principal aspects considered were

(i) the extent to which it reduces leaching of P out of the root zone,

(ii) its effect on the 'superbank' of the amended soil and whether this allows the use of soil P testing for managing P fertiliser applications, and

(iii) whether there are any health implications of using the RMG to produce food for human consumption.

Materials and Methods

For full materials and methods of each experiment, see detailed experimental reports in Appendix 1. The following is an outline of the general methods used.

Field Experiments

Sites

Site 1 : A commercial horticultural property at Anketell, W. A., approximately 30 km south of Perth. The site had been under intensive cultivation of vegetable crops for approximately 10 years. The soil was Joel sand of the Bassendean Association (desrcibed by McArthur and Bettenay 1960).

Site 2 : A commercial horticultural property at Mandogalup, W. A., approximately 30 km south of Perth. The site had been under intensive cultivation of vegetable crops for 12 years. The site was located low in the landscape, close to a swamp. The soil appeared to be a Joel sand of the Bassendean Association.

Site 3 : A commercial horticultural property at Guilderton, W. A., approximately ? km north of Perth. The site had been under intensive cultivation of vegetables for approximately 5 years. The soil was a grey-phase Karrakatta sand (described by McArthur and Bettenay 1960).

Sites 4 and 5 : Management problems of experiments on commercial properties led to experimental sites being established on the Department's Research Centre at Medina, approximately 30 km south of Perth. The soils on these sites had been previously used for pasture production, but had very low P contents. The soil type was yellow Karrakatta sand (described by McArthur and Bettenay 1960).

Red Mud

The red mud/gypsum (RMG) used on Sites 1, 2 and 3 contained 10 % gypsum (w/w) and that used on Sites 4 and 5 contained 5 % gypsum (w/w). All RMG was produced by the 'dry mix process' (i.e. gypsum mixed with red mud while red mud was dry) by Alcoa of Australia Ltd. at their Kwinana Residue Treatment Plant. However, during the first experiment on Site 4 (trial no. 92MD37), it was felt that the RMG contained insufficient gypsum to neutralise the alkalinity present in the red mud. A further 5 % gypsum by weight was applied to RMG-amended soil on Site 4 before the second experiment (93MD8) and also to Site 5 before the first experiment.

On all sites, RMG was spread manually using a front-end loader to measure the required quantity, and shovels and rakes to distribute it evenly over the plot. The RMG (and extra gypsum on sites 4 and 5) was then incorporated into the soil to a depth of approximately 30 cm, using a rotary hoe.

Experimental Designs

The design of the experiments varied but all included at least three levels of RMG, arranged in a randomised block design with three replications. Most also included 5 or 6 levels of pre-planting P applied as single superphosphate on each level of RMG, in a split-plot design.

On Site 1, there were four levels of RMG ranging from 0 to 240 t RMG/ha. In the first experiment on this site (trial no. 91PE4), five levels of P up to 320 kg P/ha were applied as single superphosphate before planting. No further pre-planting P was applied in subsequent experiments in an attempt to assess the residual value of applied P on various levels of RMG (trial nos. 92PE5, 92PE46, 93PE30).

Sites 2 and 3 received one level of P over the entire crop due to management constraints. Both sites had four levels of RMG up to 180 t RMG/ha. There was only one experiment on each of these sites (Trial 91PE44 on Site 2 and trial no. 91PE41 on Site 3).

On Site 4, the highest level of RMG was 480 t RMG/ha, as it was decided to examine a broader range of RMG levels to determine its relationship with leaf P requirement. In the first experiment on this site (trial no. 92MD37), six P levels were applied up to 800 kg P/ha. This P was used in the second experiment (trial no. 93MD8) to test residual response on RMG levels up to 120 t RMG/ha only. More P was also applied to previously unused plots on this site to compare the response to current P.

Site 5 had three levels of RMG up to 120 t RMG/ha and six levels of pre-planting P up to 400 kg P/ha. Only one experiment was conducted on this site.

Crops

A range of crops commonly grown on the Swan Coastal Plain was assessed. This included carrots (c.v. 'Topak' and c.v. 'Red Hot'), onions (c.v. 'Early Creamgold'), cabbage (c.v. 'Cameron'), Chinese cabbage (c.v. unknown), lettuce (c.v. 'Summergold'), cauliflowers (c.v. 'Arfak') and potatoes (c.v. 'Delaware').

Measurements

Measurements varied between experiments but in the field trials these generally came under four general headings : soil P and other characteristics, plant growth, plant uptake of heavy metals and radiation.

(a) Soil P and other characteristics : Bicarbonate-extractable P (Bic-P) (Colwell 1963), total P (kjeldahl digest), Phosphorus Retention Index (PRI) (Allen and Jeffery

1990), pH (H_2O), pH ($CaCl_2$) and Electrical Conductivity (EC) (1:5) in the top 15 cm of soil were normally measured both before planting and after harvest. Phosphorus Retention Index is a laboratory measure of a soil's ability to sorb P. It is affected by the amount of exchangeable P already present in the soil. The Bic-P of the soil can be used as an estimate of the amount of the exchangeable P in order to adjust the measured PRI. The adjusted PRI is referred to as PRI*. On Site 1, the total Fe and Al content (0 - 15 cm) was also measured as well as the PRI* at 15 - 30 cm and 30 - 45 cm depths.

(b) Plant growth : A leaf (or other tissue) sample was taken from each crop at an appropriate growth stage for nutrient analysis. The Youngest Mature Leaf (YML) was sampled from carrots and onions at mid-growth and from cauliflowers at buttoning. The petiole of the YML of potatoes was sampled 11 weeks after planting. In lettuce, cabbage, Chinese cabbage and cauliflowers, the Wrapper Leaf (WL) was sampled at heading or shortly thereafter.

In all experiments conducted in the first year of the project (1991), only P concentration was determined. In the second year of the project, concentrations of N, P and K were determined. In all experiments in the final year of the project (1993), the following suite of elements was measured : N, P, K, Ca, Mg, S, Fe, Mn, Zn, Cu, B, Mo and Na.

The concentration of Cl was also determined in lettuce (92MD37) and potatoes (93MD9).

Total and marketable yield was measured for each crop, and P removal in the harvested product determined for lettuce and cauliflowers (93MD8).

(c) Plant uptake of heavy metals : Samples were taken from the edible portion of each crop at harvest and were analysed for their heavy metal content. The heavy metals analysed were : Cd, Ni, Pb and Cr in the first (carrot) trial (trial no. 91PE4). In all other trials, the following suite of metals was analysed : Sb, As, Ba, Cd, Cr, Co, Cu, Pb, Hg, Mo, Ni and Se.

(d) Radiation :

The following suite of radio-nuclides was measured in lettuce, cauliflowers, potatoes and cabbage : U-238, Th-228, Ra-226, Ra-228, Pb-210, K-40 and Cs-137. Caesium-137 is a product of nuclear fallout and is not related to the level of RMG in the soil. These radio-nuclides were measured by high-resolution gamma ray spectrometry.

Glasshouse Experiments

A preliminary column study was carried out before the start of the project, however, the results will be reported here as they complement the results of the project. This study measured directly the ability of a Joel sand amended with RMG up to 256 t/ha to retain P, NO_3-N, NH_4-N and K. These nutrients were measured in soil and leachate. The activity of radio-isotopes were measured in the soil (Th-232, Ra-226 and K-40) and in the leachate (Ra-226 and Ra-228).

A germination experiment examined the germination of carrots, onions, lettuce and Chinese cabbage in 120 t RMG/ha, both leached and unleached of salts, as well as in several other types of red mud. The pH, EC and ionic composition of each soil treatment was measured.

Results and Discussion

Presented below is a summary of the major results obtained from the project. For further information on the results from a particular experiment, please refer to the appropriate experimental report in Appendix 1.

Phosphorus Retention Index (PRI)*

The PRI* of unamended soil varied between sites (Table 1). Based on these PRI* values, the soils on Sites 4 and 5 and in the column study can be described as 'very weakly adsorbing' (Allen and Jeffery 1990). These values are typical of virgin sands (McPharlin *et al.* 1990). The PRI* values of the cultivated sites (i.e. Sites 1 to 3) are higher than would be expected on a virgin soil of the same type (McPharlin *et al.* 1990) and probably result from the addition of organic matter and iron (in water and fertilisers) to the sites over several years of cultivation. However, the soils on Sites 1 and 3 can still be described as only 'weakly adsorbing' (Allen and Jeffery 1990). The PRI* on Site 2 is higher than would normally be expected even from a Spearwood sand (approximately 7; McPharlin *et al.* 1990). It is therefore possible that this soil was not a true Joel sand. As a result, little effect of RMG on soil properties would be expected on this site.

Table 1. The Phosphorus Retention Index (PRI*) of unamended soil on five field sites and in a glasshouse column study.

Site	Soil type	History	PRI*
1†	Joel	cultivated	4.2
2	Joel ?	cultivated	11.4
3†	grey Karrakatta	cultivated	4.6
4‡	yellow Karrakatta	virgin	2.2
5	yellow Karrakatta	virgin	2.0
column	Joel	virgin	<0.1

† Averaged over two measurements.

‡ 0 kg P/ha plots only; averaged over 4 measurements.

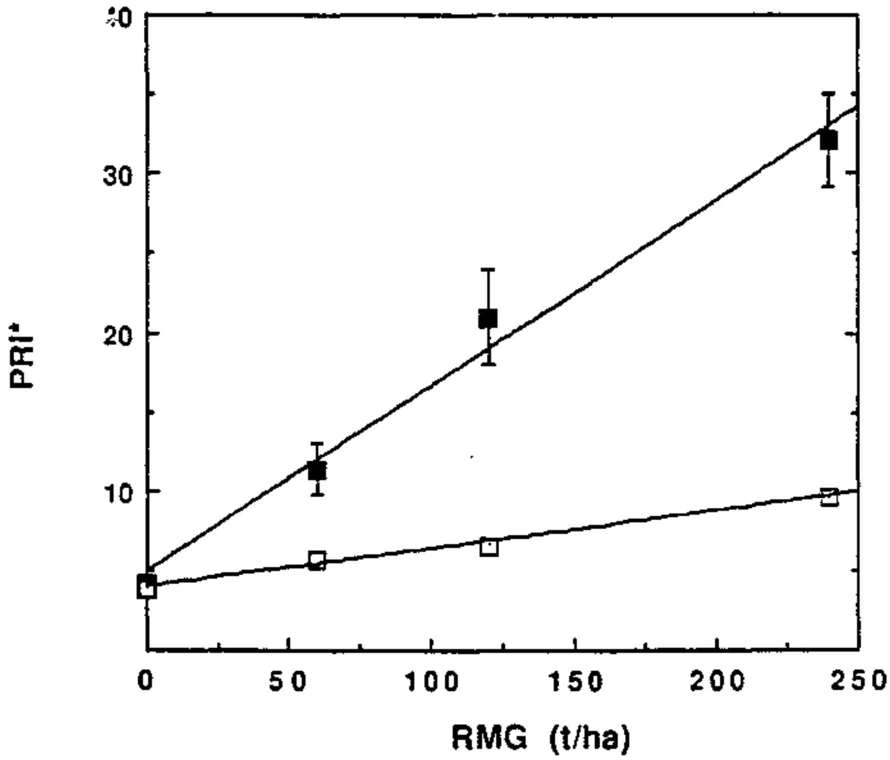

Fig. 1. Mean Phosphorus Retention Index (PRI*) (0 - 15 cm) vs. level of RMG at sowing (■) and 4 months after harvest (□) of carrots (c.v. 'Red Hot').

The PRI* of amended soil on Site 1 (trial no. 91PE4) showed a good curvilinear relationship with the iron and aluminium content of the soil one month after the application of RMG ($y = 1.64 + 2.78x + 0.21x^2$; $R^2 = 0.92$). However, the relationship with level of RMG was much more variable (Fig. 1). The PRI* on Site 1 decreased and became less variable over time.

This suggests that the RMG was poorly incorporated into the soil when first applied but that repeated hoeing over time improved the incorporation. The PRI* measured over time was also linearly correlated with the EC (1:5) of the soil measured over time ($y = 4.84 + 14.3x$; $R^2 = 0.76$). Previous work has shown that the residual salinity in RMG is mostly caused by gypsum (Ho 1989). Soils where the dominant cation is Ca^{2+} have been shown to adsorb substantially more P than those where the dominant cation is K^+ or Na^+ (Barrow 1984, Curtin *et al.* 1992). The excess Ca from the gypsum may then be the cause of the high initial PRI* values, and as the excess gypsum was leached from the soil, so the PRI* decreased. This may have also reduced the variability in the measured PRI*.

Table 2 shows the average increase in PRI* above that of unamended soil when 120 t RMG/ha was added to each site. Where possible, the PRI* measured several months after the application of RMG has been used. The increase is based on a linear regression fitted to the relationship between mean PRI* and level of RMG.

Table 2. The mean increase in PRI* (0 - 15 cm) of soil amended with 120 t RMG/ha on five field sites and in soil mixes for a glasshouse column study.

Site	Gypsum (% w/w)	Months after application	Increase in PRI*
1	10	10	2.9
2	10	0	5.8
3	10	4	4.3
4	5	2	2.6
5	5	4	1.3
Column	10	24	4.1

The increase in PRI* was relatively uniform between sites. As the PRI* on Site 2 was not measured after leaching, it would be expected to be slightly higher than on the other sites. Generally, 120 t RMG/ha increased PRI* by 3 to 4 units compared with unamended soil, regardless of the PRI* of the unamended soil, except for Site 5, where the increase was only about 1 unit. Why Site 5 should have been different from the others is not known.

Electrical Conductivity

The EC (1:5) (0 - 15 cm) on all sites, measured on 0 kg P/ha plots, increased significantly with level of RMG when the RMG was first applied. However, it also decreased on all sites after some leaching. For example, on Site 4 (trial no. 92MD37), the EC immediately after RMG application increased with level of RMG from 4 mS/m on unamended soil to 59 mS/m on 240 t RMG/ha and 127 mS/m on 480 t RMG/ha. After 30 days, the EC was only 15 mS/m on 240 t RMG/ha and 16 mS/m on 480 t RMG/ha (Fig. 2).

The EC of amended soil after leaching was similar on other sites (Table 3). No measurement of EC on Site 2 was taken at the end of the crop.

Table 3. The Electrical Conductivity (1:5) (mS/m) of the top 15 cm of soil amended with red mud/gypsum (RMG) on three field sites after leaching.

RMG (t/ha)	Site 1 11 months† 92PE5	Site 5 1.5 months 93MD9	RMG (t/ha)	Site3 4 months 91PE41
0	5	7	0	8
60	6	10	90	17
120	10	11	135	17
240	12		180	21

† Months after application of RMG.

These EC values are low and no reductions in yield were observed which could be attibuted to salt toxicity. Levels of EC (0 - 15 cm) on Site 3 shortly after RMG was applied (trial no. 91PE41) ranged from 15 mS/m on unamended soil to 35 to 40 mS/m

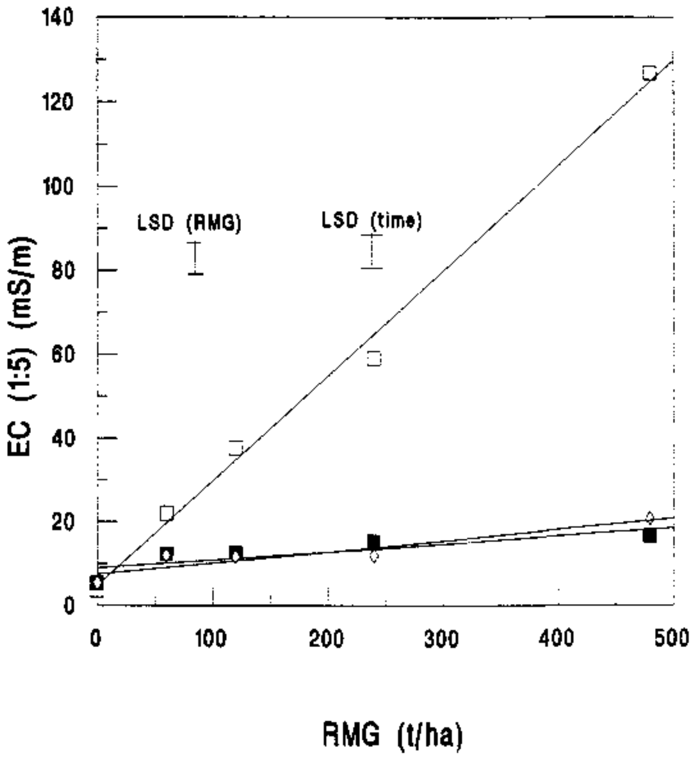

Fig. 2. The Electrical Conductivity (EC) (1:5) (0 - 15 cm) where no P fertiliser was applied vs. level of RMG at 2 (□), 30 (■) and 60 (◇) days after the application of RMG.

on amended soil (data not shown). This may have been responsible for the chlorosis observed in the tips of young onion seedlings at 35 days after sowing. This chlorosis was no longer evident at 52 days after sowing.

Soil pH

The pH (H_2O) and pH ($CaCl_2$) of the top 15 cm of soil on all sites increased with level of RMG in a trend which could be described by a Mitscherlich curve (e.g. Site 1; Fig. 3).

The only exception to this was Site 2, where pH (H_2O) did not increase significantly between levels of RMG. The magnitude of the increase between 0 and 60 t RMG/ha or 0 and 90 t RMG/ha was between 1 and 2 units on all sites except site 2 (Table 4). No increase could be calculated for Site 4 as the pH of unamended sand was very variable (trial no. 92MD37).

Table 4. The increase in the pH (H_2O) of the top 15 cm of soil on several sites when amended with 60 or 90 t RMG/ha†.

Site	Soil type	History	Increase in pH
1	Joel sand	cultivated	1.5
3	grey Karrakatta sand	cultivated	1.2
5	yellow Karrakatta sand	virgin	1.1
column	Joel sand	virgin	1.7

† Values refer to 90 t RMG/ha on Site 3 and 60 t RMG/ha on all other sites.

The fact that the increase in soil pH is relatively uniform means that the effect of RMG addition on the pH of a site can be predicted. The lack of increase in soil pH on Site 2 was probably related to the reasons for its high PRI*. The soil was apparently very well buffered to changes in pH, either because of the additions of organic matter or because of some differences in soil type.

The actual pH of amended soil varied between sites, depending largely on the pH of the unamended soil. On Sites 1 and 3 (trial nos 91PE4 and 91PE41), the pH (H_2O) reached a maximum of about 8, while on Sites 4 and 5, the maximum was between 8.5 and 9 (trial nos 92MD37 and 93MD9). In the column study, a maximum was not

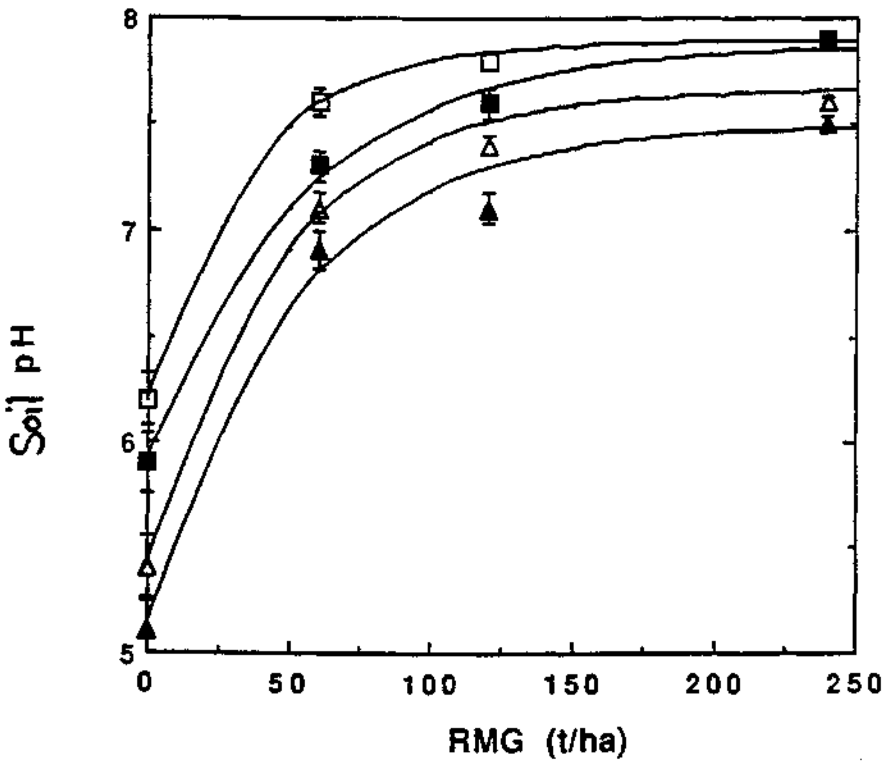

Fig. 3. Soil pH (0 - 15 cm) measured in water (squares) and 0.01 M $CaCl_2$ (triangles) on Site 1 at sowing (open symbols) and harvest (closed symbols) of carrots (c.v. 'Red Hot') vs. level of RMG.

reached but pH (H_2O) at 256 t RMG/ha was only 7.2 (data not shown). These maximum pHs, particularly those on Sites 4 and 5, are high for most crops. Some crops, such as potato, are particularly sensitive to such pHs (Mattaboni 1990).

A small decrease of 0.2 to 0.3 of a unit was observed on Site 1 between sowing and harvest of the first crop (Fig. 3) but no decrease was observed on any other site. The long term effects of RMG on soil pH were not observed in this project. Ward (unpublished data) observed that the pH of soil amended with up to 2000 t RMG/ha and cropped to medics and clover did not change over 8 to 10 years. However, more fertilisers are applied to horticultural crops than to pasture so the potential for a reduction in soil pH is greater on horticultural crops.

Bicarbonate-extractable P

Red mud amendment did not increase the 'background' Bic-P of the soil. For example, on Site 1, Bic-P was 25 to 33 ug/g on all amended and unamended soil before any pre-planting P was applied (trial no. 91PE4). On Site 4, the Bic-P before planting ranged from 7 to 17 ug/g and did not differ significantly between RMG levels (trial no. 92MD37).

On all sites, except Site 2, RMG amendment increased the Bic-P in the top 15 cm of soil at the end of the first crop, relative to unamended soil. Table 5 shows the Bic-P levels in the top 15 cm of soil after the harvest of several crops when approximately 150 to 200 kg P/ha was applied. The data for cauliflowers on Site 4 refer to the currently-applied P in that experiment. In all cases, Bic-P increased by between 9 and 18 ug/g between 0 and 60 or 0 and 90 t RMG/ha. On all sites, Bic-P was the same on all levels of amended soil. Bic-P on Site 2 was very high (mean of 120 ug/g at harvest) on all treatments (trial no. 91PE44; not included in Table). This can be attributed to the high PRI of the unamended soil. Soil P was not measured on Site 5.

Table 5. Bicarbonate-extractable P (0 - 15 cm) (ug/g) at the harvest of several crops on three sites amended with red mud/gypsum (RMG) at moderate levels of P application†.

RMG (t/ha)	Site 1 91PE4 Carrots	Site 4 92MD37 Lettuce	Site 4 93MD8 Cauliflowers	RMG (t/ha)	Site 3 91PE41 Onions
0	24	22	17	0	42
60	38	31	29	90	60
120	43	33	38	135	69
240	38	34	-	180	64
480	-	35	-		

† P applications varied. For 91PE4 160 kg/ha pre-plant, 26 kg/ha post-plant; 91PE41 61 kg/ha pre-plant, 84 kg/ha post-plant; 92MD37 and 93MD8 : 200 kg/ha pre-plant, 0 kg/ha post-plant.

At higher P applications (300 to 400 kg/ha) Bic-P on amended soil was approximately 50 to 60 ug/g on all levels of RMG (Table 6). However, the difference between unamended and amended soil varied from 30 ug/g in the column study and in the cauliflowers on Site 4 to 13 ug/g in the lettuce crop. When the relationship between Bic-P and level of RMG on Site 1 is extrapolated, the difference between unamended and amended soil on that site would also be approximately 30 ug/g.

Table 6. Bicarbonate-extractable P (0 - 15 cm) (ug/g) at the harvest of several crops on three sites amended with red mud/gypsum (RMG) at high levels of P application†.

RMG (t/ha)	Site 1 91PE4 Carrots	Site 4 92MD37 Lettuce	Site 4 93MD8 Cauliflowers	Column No crop
0	-	34	25	12
60	-	47	54	42
120	62	72	56	46
240	64	57	-	58
480	-	46	-	-

† P applications varied. For 91PE4 320 kg/ha pre-plant, 26 kg/ha post-plant; 92MD37 and 93MD8 400 kg/ha pre-plant, 0 kg/ha post-plant; Column 320 kg/ha in a single application.

On Sites 1 and 4, the residual Bic-P from the first experiment (trial nos. 91PE4 and 92MD37) was measured 2 and 4 months later, respectively, at the planting of the second experiment (trial nos. 92PE5 and 93MD8). On both of these sites, the Bic-P decreased significantly between the harvest of the first experiment and the planting of the second. Table 7 shows residual Bic-P on these sites when approximately 200 kg P/ha was applied ('moderate P application') and when 350 to 400 kg P/ha was applied ('high P application').

At moderate P levels, the increase between 0 and 60 t RMG/ha was less than 10 ug/g on both sites. At high P levels, Bic-P on amended soil was only 30 to 40 ug/g on both sites. There was no difference in Bic-P between levels of RMG on amended soil.

Table 7. Residual Bicarbonate-extractable P (0 - 15 cm) (ug/g) several months after the harvest of crops on two sites amended with red mud/gypsum at moderate# and high* levels of P application.

	Moderate P application		High P application	
RMG	Site 1†	Site 4‡	Site 1	Site 4
(t/ha)	92PE5	93MD8	92PE5	93MD8
0	19	18	-	32
60	26	23	-	34
120	31	27	36	37
240	30	-	40	-

92PE5 186 kg P/ha; 93MD8 200 kg P/ha.

* 92PE5 346 kg P/ha; 93MD8 400 kg P/ha.

† Previous crop 91PE4, harvested 4 months earlier

‡ Previous crop 92MD37, harvested 2 months earlier.

The increases in Bic-P on amended soil are disappointing, particularly at levels of P which are normally applied in the field (i.e. 150 to 200 kg P/ha). The reason for this small increase is not fully understood. Possible explanations are : firstly that the poor mixing of the RMG throughout the soil reduced the effective P adsorption of the RMG. On Site 1, approximately 48 % of the RMG was found to exist in aggregates of greater than 2 mm diameter, 9 months after the RMG was first applied, thus reducing the adsorptive area. Such poor mixing is to be expected when field equipment is used. However, the increase in Bic-P in the column study, where RMG was mixed uniformly with the soil, was similar to that observed in the field.

Secondly, the poor mixing may have increased the variation in the measured Bic-P so that the mean values were not significantly different from each other. The presence of aggregates of RMG in amended soil would have caused the extremes of measured Bic-P to have been similar on all RMG levels.

Thirdly, theoretical calculations (Jeffery pers. comm.) indicate that an increase in PRI* of 1 unit should increase Bic-P by approximately 10 ug/g. This coincides with the observed increase of 10 to 20 ug/g between 0 and 60 or 0 and 90 t RMG/ha at the end of the first crop, where the PRI* increased by 1.5 to 2 units on average. However, this cannot account for the reduction in Bic-P between the first and second crops. This decrease could have been caused by leaching of P or by soil reactions which reduced the availability of P to the plants. Further laboratory experiments are required to resolve this question.

Soil-testing requires that the top 15 cm of soil hold sufficient plant-available P at the time of planting of the crop to allow maximum (or 99 % of maximum) yield. This varies between crop and also between soil type. Values determined on a yellow Karrakatta sand are 60 ug/g for carrots (McPharlin *et al.* 1994b) and 55 ug/g for cauliflowers (McPharlin unpublished data). Even when 350 to 400 kg P/ha was applied, the Bic-P levels on amended soil at the beginning of the second crop were less than this. As the PRI* of yellow Karrakatta sand is similar to that of amended soil (McPharlin *et al.* 1990), soil-testing is apparently not viable on amended soil. However, the RMG may react differently with applied P than does a yellow sand. The appropriate Bic-P values on RMG-amended soil may therefore be different from those on the sand. It is also important to note that the relationship between Bic-P and that P which is actually available to the plant is not fully understood for RMG-amended soil. More research is needed into these aspects of RMG amendment before soil-testing can be used as a P management tool in a commercial situation.

Another problem for soil-testing on amended soil is the poor mixing of the RMG and the variation it causes in the measured Bic-P level. A farmer could not be sure that the measured Bic-P level of his soil was an accurate reflection of the actual Bic-P level.

Total and fertiliser P

The addition of RMG to the soil increased the 'background' P on Sites 1 (trial no. 91PE4) and 4 (trial no. 92MD37) but not on Site 5 (trial no. 93MD9) (Table 8). The initial total P measurements on Sites 2 and 3 were taken after the pre-planting P had been applied so the effect of RMG on 'background' total P cannot be determined.

Table 8. Total P (0 - 15 cm) (ug/g) on three sites amended with red mud/gypsum (RMG) before the application of pre-planting P.

RMG (t/ha)	Site 1 91PE4	Site 4 92MD37	Site 5 93MD9
0	89	69	43
60	100	62	52
120	-	91	50
240	163	103	-
480	-	163	-

In the column study, where P leaching was measured directly from the leachate collected beneath each column, RMG at 64, 128 and 256 t/ha reduced P leaching by 49 %, 59 %, and 85 % relative to unamended soil (Fig. 4). Of the P which was not leached, 90 % remained in the top 20 cm of soil. This was based on an application of 320 kg P/ha leached at 34 mm/day.

In the field, measurements of P leaching or retention were less clear because they were measured indirectly using soil measurements of total P. The addition of P in the RMG itself also complicated these measurements. On Site 1 the amount of fertiliser P (i.e. total P - 'background' P) retained in the top 15 cm of soil at harvest (trial no. 91PE4) was too variable to allow any conclusions to be reached. However, 4 weeks after the application of pre-planting fertiliser, the top 15 cm of soil held 54 kg/ha of fertiliser P on unamended soil, compared with 196 and 164 kg/ha on 60 and 240 t RMG/ha when 160 kg P/ha was applied. This amounts to approximately one-third of the applied P being lost from the top 15 cm of unamended soil within one month of fertiliser application, while amended soil still held 100 % of the applied P. Plant growth at this stage was minimal.

Retention of fertiliser P on Site 4 at the end of the first experiment (trial no. 92MD37; lettuce) and on the currently-applied P treatment at the end of the second experiment (trial no. 93MD8; cauliflowers) increased between 0 and 120 t RMG/ha. For example, at the end of the first crop, the amount of fertiliser P retained at 200 kg P/ha increased from 77 kg/ha on unamended soil to 117 kg/ha on 120 t RMG/ha. At the end of the second crop, the amount of currently applied fertiliser P retained

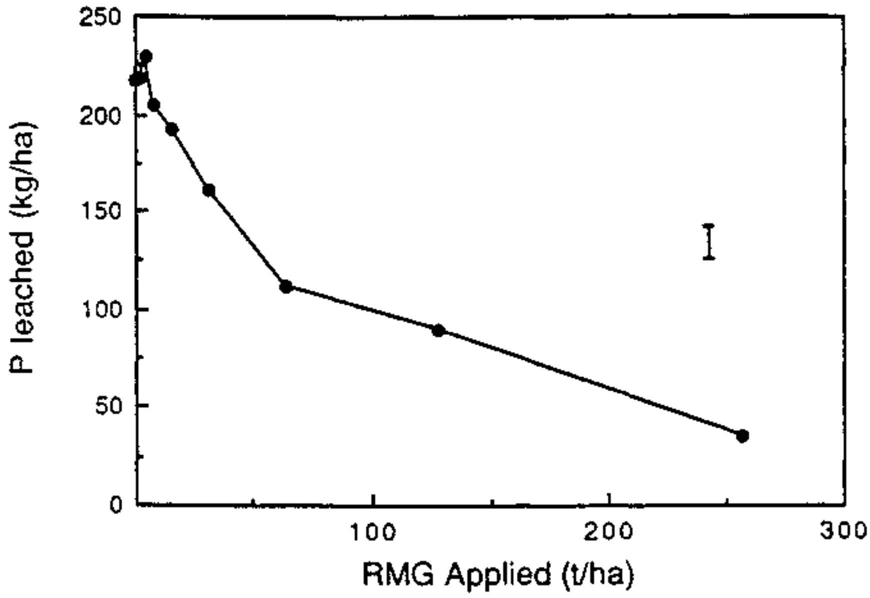

Fig. 4. Phosphorus (P) leached from a Joel sand amended with different rates of RMG in a column study.

increased from 43 kg/ha on unamended soil to 122 kg/ha on 120 t RMG/ha (data not shown).

However, when the amount of applied P taken up by the harvested product was considered, the variation increased so that there was no longer any significant difference between 0 and 120 t RMG/ha, although there was still an upward trend (Table 9). All of the applied P was therefore accounted for at 240 and 480 t RMG/ha in the lettuce crop, and possibly also on 120 t RMG/ha as the highest observed proportion accounted for on 120 t RMG/ha was 93 %.

The lower P retention in the cauliflowers may have been because the 'crop removal' figure only included the curd, and not the leaves and stem. Also, the crop was grown in winter whereas the lettuce was grown in summer when leaching would be expected to be less.

Table 9. The proportion (%) of fertiliser P accounted for in the top 15 cm of soil at harvest or in the harvested product from a crop of lettuce (c.v. 'Summergold') and a crop of cauliflowers (c.v. 'Arfak') grown on two sites amended with red mud/gypsum (RMG). Mean values are averaged over several levels of applied P.

	Lettuce			Cauliflowers		
RMG	Mean	Max.	Min.	Mean	Max.	Min.
0	53	82	33	29	44	18
60	39	64	10	34	57	- 11
120	75	93	66	55	72	36
240	123	192	82	-	-	-
480	95	124	69	-	-	-

It is apparent that RMG does improve the ability of the poor soils to hold P in the root zone and that a level of RMG of at least 120 t RMG/ha is required. However, the data do not give a satisfactory indication of the quantitative effect of RMG on the leaching of applied P in the field, because of the variation involved. This variation is largely due to the uneven incorporation of the RMG, and is exacerbated by the presence of P in the RMG itself. More direct measurements are required, such as the P content of water in drains running off horticultural properties. The only property where this has been done (not included in report) did not give any meaningful data as amended and unamended areas were not planted with the same crops at the same time and often received different fertiliser applications.

Emergence

The emergence of carrots (trial no. 91PE4) and onions (trial no. 91PE41) was observed in the field. Carrot emergence increased with level of RMG so that the final difference in number of emerged seedlings between 0 and 240 t RMG/ha was 2 to 3 plants per metre of double row (data not shown). This equates to approximately 80 000 plants per hectare, which was equivalent to a yield difference of 6 to 8 t/ha, based on the yield observed in that experiment. This was less than the variation observed in total and marketable yields, so would not have affected the conclusions made about the yield effects of RMG. It is not known what could have caused this increase in emergence on amended soil. Possible factors include the soil's water retention or its pH.

There was no significant effect of RMG on the emergence of onions, although there was a trend for the number emerged to decrease at 135 and 180 t RMG/ha at 18 days after emergence (Fig. 5). At 35 days after emergence, there was no longer any apparent difference between levels of RMG. This indicates that the higher levels of RMG slowed down the emergence of onions but did not affect the final number of seedlings emerged. This effect on onions has been observed previously at high level of EC (Wannamaker and Pike 1987). The EC values observed at sowing on this site were sufficient to cause yield reductions of 50 % or more in onions (Mattaboni 1990). It is therefore advisable to leach amended soil thoroughly before sowing onions.

In the glasshouse germination experiment, lettuce emergence was not affected by 120 t RMG/ha, either leached or unleached (Table 10). There was a trend for emergence to be 20 % less on unleached 120 t RMG/ha than on leached 120 t RMG/ha, however it is not clear whether this difference represented a real effect. For carrots and Chinese cabbage the results are difficult to interpret as the emergence in the controls was less than would normally be expected in the field (Table 10). However, the emergence of Chinese cabbage seedlings, and to a lesser extent the carrots, on 120 t RMG/ha was very close to the germination observed for these crops in de-ionised water. This suggests that 120 t RMG/ha, either leached or unleached, did not have an adverse effect on the emergence of these crops. No results could be obtained for onions as the seed batch used had only 25 to 30 % germination in de-ionised water.

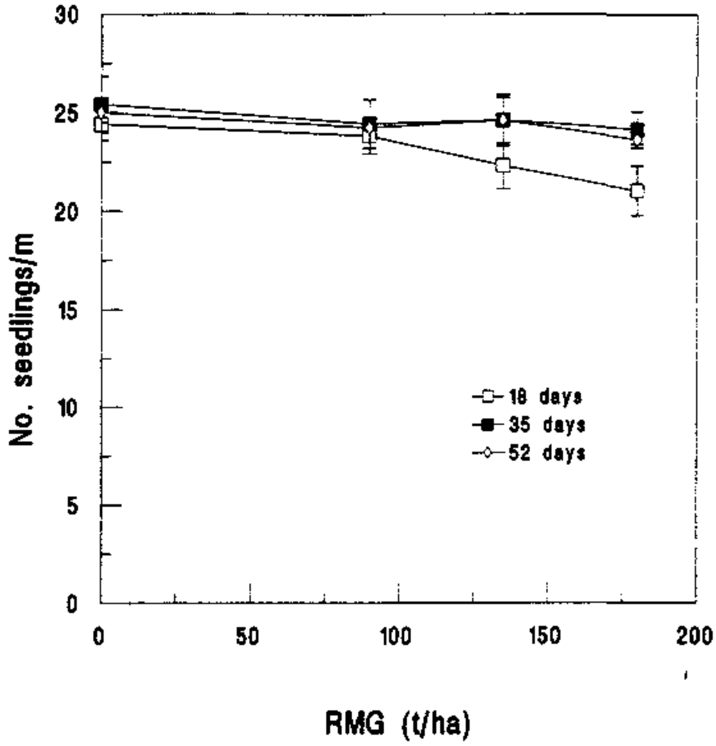

Fig. 5. Number of onion (c.v. 'Creamgold') seedlings emerged in a 1 m length of a double row at 18 (□), 35 (■) and 52 (◇) days after sowing vs. level of RMG.

Overall, then, it could be concluded that 120 t RMG/ha is safe for germinating a range of vegetable crops commonly grown from seed on the Swan Coastal Plain, although a wise precaution would be to leach the RMG before sowing.

Table 10. Final emergence (%) of lettuce, carrot and Chinese cabbage on 120 t red mud gypsum (RMG)/ha in both leached and unleached states, compared with that on a Joel sand.

Treatment	Lettuce	Carrot	Chinese cabbage
Sand	88	53	59
Sand + lime†	87	40	64
120 t RMG/ha (unleached)	79	72	97
120 t RMG/ha (leached)	100	83	92
Significance	**	NS	***
LSD (5 %)	21		32

† Lime equal to the liming potential of 120 t RMG/ha (based on assumption of RMG having liming potential equivalent to 10 % that of $CaCO_3$)

Plant response to currently-applied P

The responses of the crops to currently-applied P can be placed into three groups. The first group includes the crops on Site 1, i.e. carrots (trial no. 91PE4), Chinese cabbage (trial no. 92PE5) and cabbages (trial no. 93PE30). The Chinese cabbage and cabbage crops were grown using the P residual from the carrots. However, as post-planting P was applied throughout the crop, their growth responses are really responses to currently-applied P. The second group includes crops grown on Sites 3, 4 and 5, i.e. onions (trial no. 91PE41), lettuce (trial no. 92MD37), cauliflowers (trial no. 93MD8) and potatoes (trial no. 93MD9). The third group is the carrots grown on Site 2 (trial no. 91PE44).

Site 1. No crop on this site showed any yield response to level of RMG or to level of applied P. However, on all crops the concentration of the P in the Youngest Mature Leaf (YML) or Wrapper Leaf (WL) at mid-growth or heading decreased on amended soil. There was no difference in P concentration between levels of RMG on amended soil. The best example of this was in the carrots (Fig. 6). Here, the P concentration in

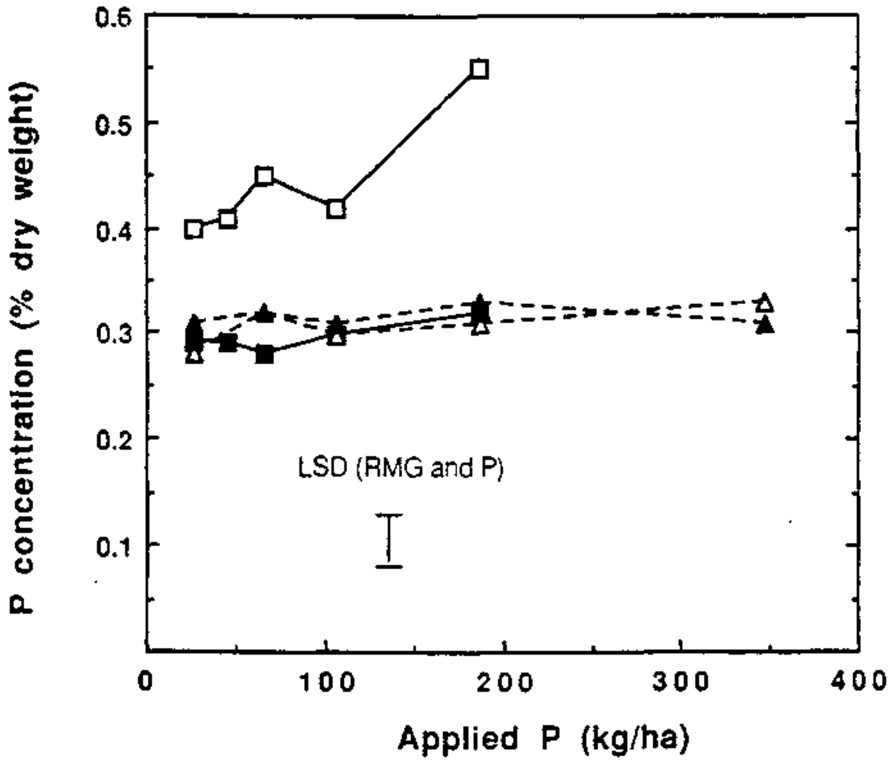

Fig. 6. Phosphorus (P) concentration in the youngest mature leaf of carrots (c.v. 'Red Hot') sampled at mid-growth vs. level of applied P at 0 (□), 60 (■), 120 (△) and 240 (▲) t RMG/ha.

the YML at mid-growth was deficient for maximum yield in plants grown on amended soil. This was reflected in noticeably reduced plant growth during the first half of the crop's growth in plants grown on amended soil. Purpling of older leaves was also observed in plants on 120 and 240 t RMG/ha during the early stages. These growth differences disappeared during the second half of growth. A similar 'catch-up' in growth was observed in the Chinese cabbage.

Sites 3, 4 and 5. These crops showed a yield response to level of RMG. The concentration of P in the leaf tissue decreased more or less uniformly at increasing level of RMG but in lettuce and cauliflower, this was overcome by increasing the level of applied P (Fig. 7a, b). In cauliflowers, the fitted Mitscherlich curves suggested that the maximum P concentration at 120 t RMG/ha was less than at either 0 or 60 t RMG/ha. However, the data points show that P concentration at 800 kg P/ha was approximately equal on all levels of RMG. The availability of P to the plant was therefore reduced by RMG amendment. As there was only one level of P applied to the onions, it cannot be determined whether the reduced P concentration was a result of reduced P availability.

In the lettuce and the cauliflowers, the reduced P availability was reflected in higher levels of P application being required for 99 % of maximum yield as the level of RMG increased. Yield of lettuce did not maximise at 480 t RMG/ha, even when 800 kg P/ha was applied (Fig. 8). Amendment with RMG at 60 t/ha increased the maximum yield of lettuce by 15 t/ha. This was apparently due to increased water uptake by the crop, as there was no difference in maximum dry weight yield between levels of RMG (Fig. 9). Even in dry weight yield the level of P required for 99 % of maximum yield increased at levels of RMG of greater than 60 t/ha. As a result of the increased maximum fresh weight yield, the farmer is economically better off with amended soil, as the increased returns far outweigh the increased P inputs. However, such an increase in yield was only observed in the lettuce, probably since it was a leafy crop grown in summer.

The maximum yield of cauliflowers was 5 t/ha less at 120 t RMG/ha than at either 0 or 60 t RMG/ha. However, the data points again show that yield at 800 kg P/ha was approximately equal at all levels of RMG (Fig. 10). The level of P required for 99 % of maximum yield increased with level of RMG, from 326 kg P/ha on unamended soil to 431 kg P/ha at 120 t RMG/ha.

A level of P application of 400 kg P/ha was not sufficient to overcome the reduction in P availability in potatoes (Fig. 11). The maximum yield of potatoes decreased at increasing level of RMG. The decrease was by 3 t/ha between 0 and 60 t RMG/ha (not significant) and by a further 7 t/ha between 60 and 120 t RMG/ha (significant at 5 %) (Fig. 12). The decrease between 0 and 60 t RMG/ha may have

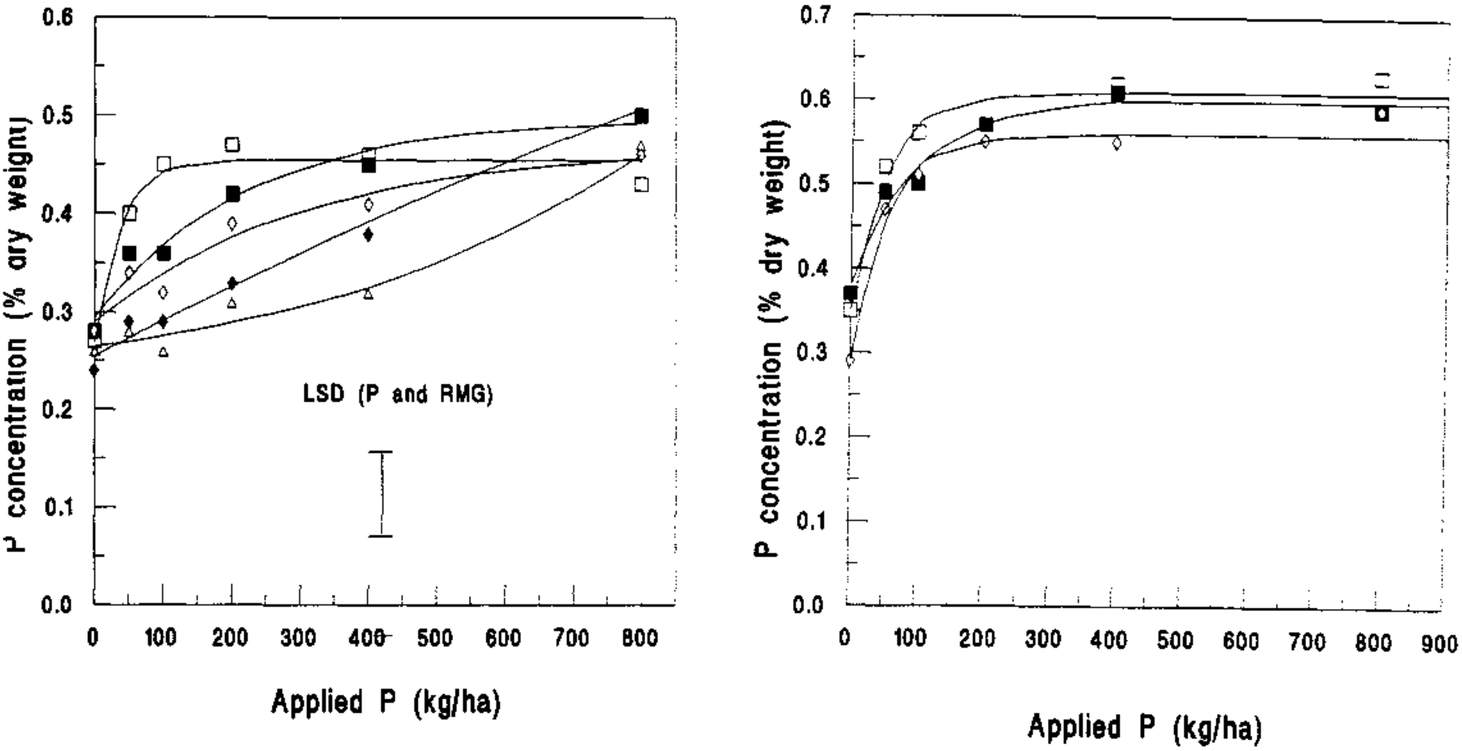

Fig. 7. Concentration of phosphorus (P) in the wrapper leaf of (a) lettuce (c.v. 'Summergold') and (b) cauliflowers (c.v. 'Arfak') sampled at heading and buttoning, respectively, vs. level of currently-applied P at 0 (□), 60 (■), 120 (◇), 240 (◆) and 480 (△) t RMG/ha. RMG was not applied on the cauliflowers at 240 and 480 t RMG/ha.

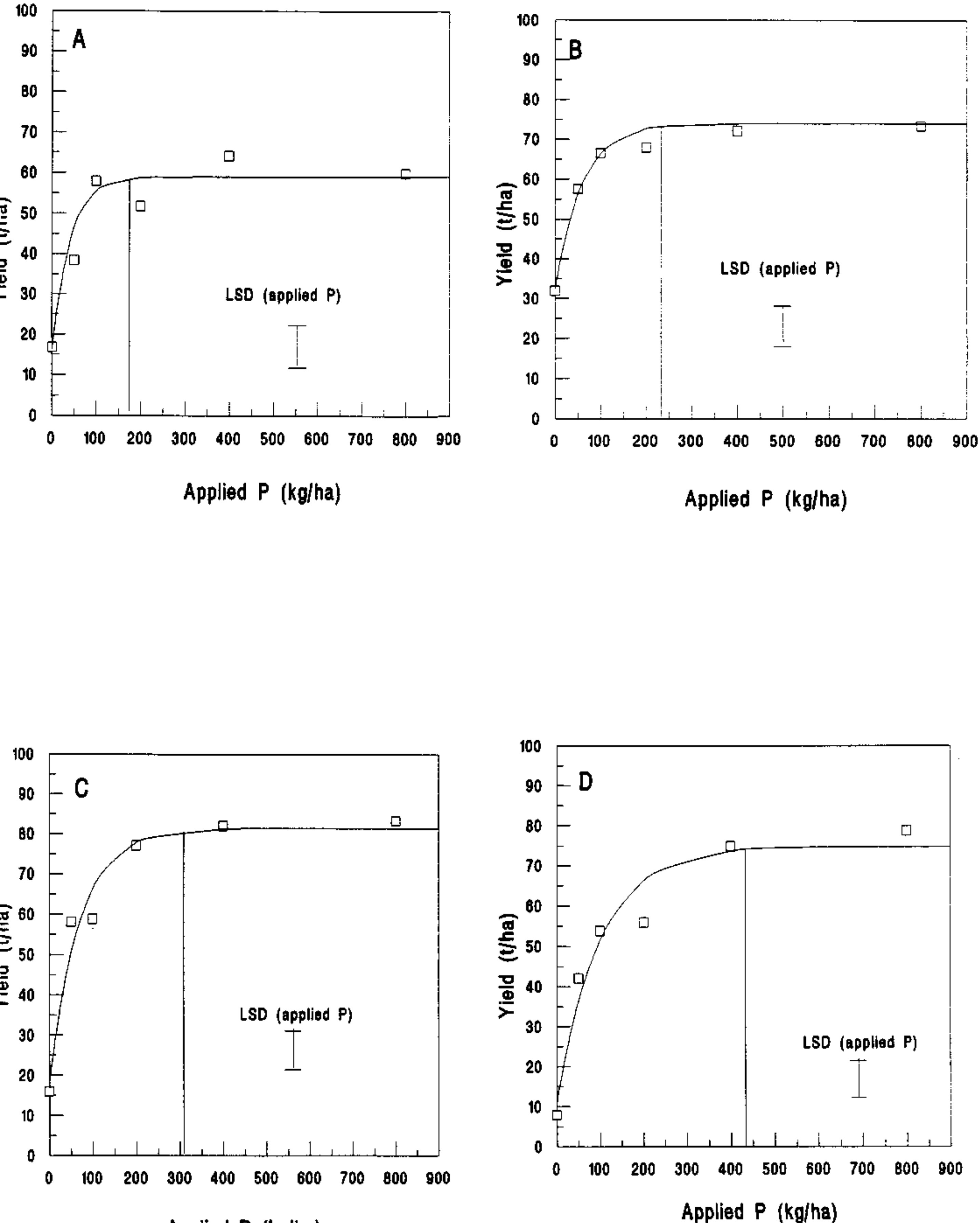

Fig. 8. Total (fresh weight) yield of lettuce (c.v. 'Summergold') vs. level of applied P (PTO).

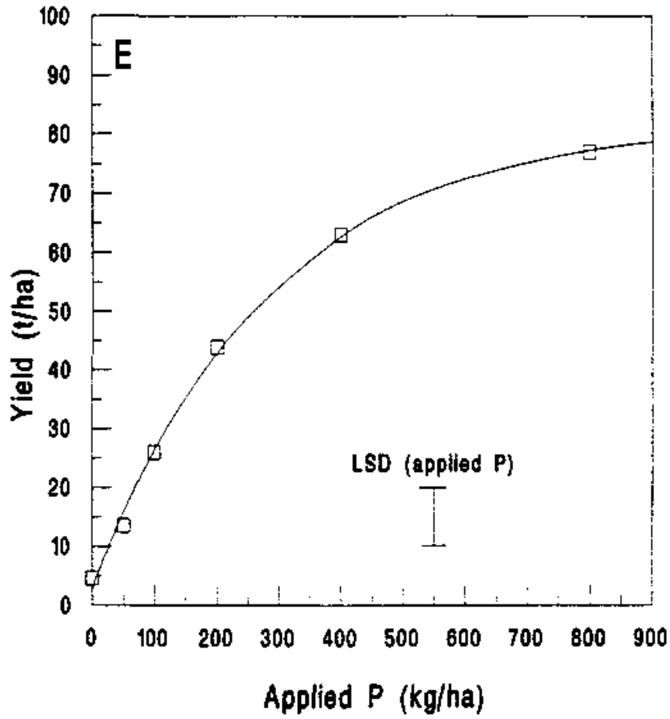

Fig. 8. Total (fresh weight) yield of lettuce (c.v. 'Summergold') vs. level of currently-applied P on (a) 0, (b) 60, (c) 120, (d) 240 and (e) 480 t RMG/ha.

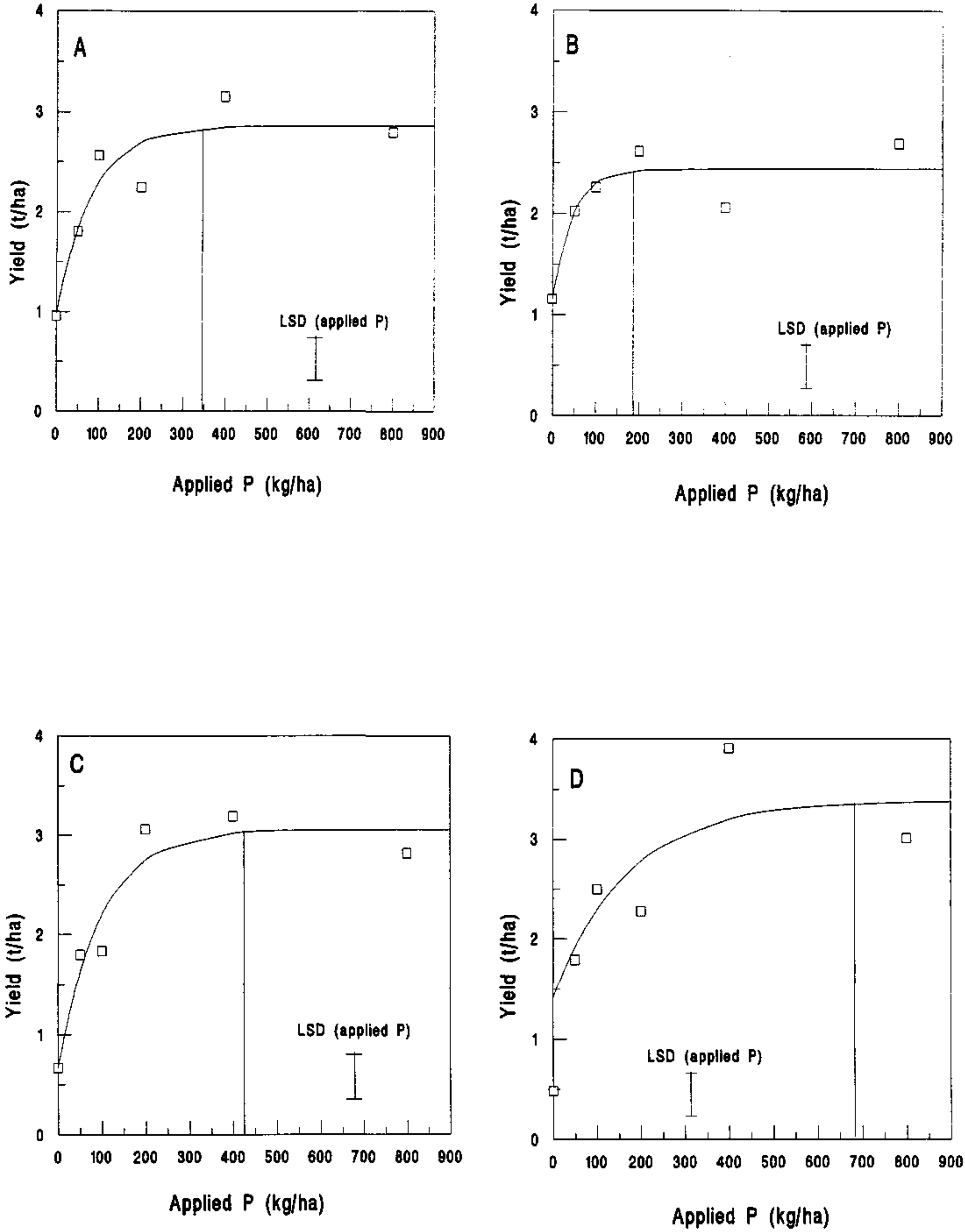

Fig. 9. Total dry matter yield of lettuce (c.v. 'Summergold') vs. level of currently-applied P (PTO).

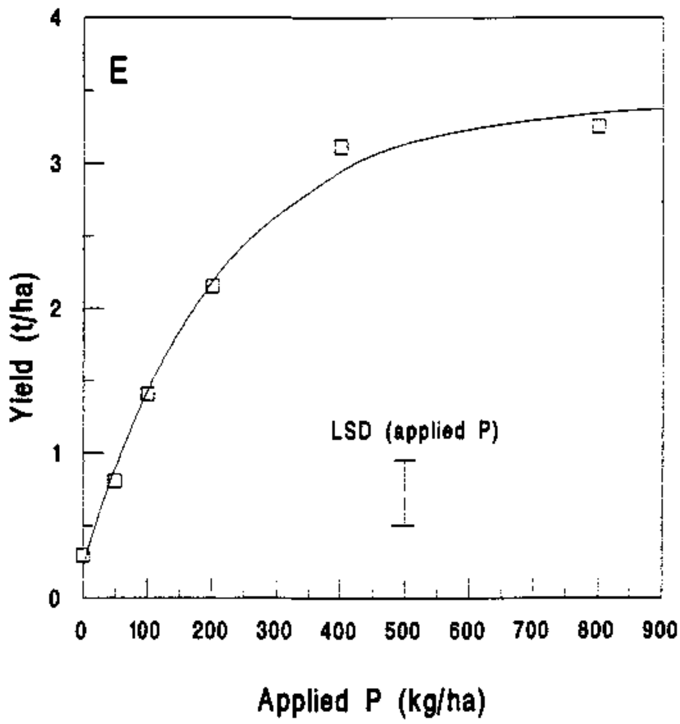

Fig. 9. Total dry matter yield of lettuce (c.v. 'Summergold') vs. level of currently-applied P on (a) 0, (b) 60, (c) 120, (d) 240 and (e) 480 t RMG/ha.

been a result of the reduced P concentration in the petiole of the YML, although it is not clear what stage of growth the potatoes were at when the sample was taken so the P concentrations cannot be compared with standards. However, there was no decrease in P concentration between 60 and 120 t RMG/ha, so the decrease in yield between 60 and 120 t RMG/ha must have been due to some other factor.

What this other factor was is not clear, but it may have been related to the increase in pH observed on amended soil. The pH of the soil (0 - 15 cm) at 120 t RMG/ha was 8.8 in water and 8.1 in 0.01 M $CaCl_2$ which is much higher than the optimum pH for potatoes of 4.5 to 6 (Mattaboni 1990). However, the pH at 60 t RMG/ha was almost as high, being 8.6 in water and 7.8 in $CaCl_2$. Any pH effect should therefore have also been observed at 60 t RMG/ha as well. No nutrient deficiencies were observed so if it was a pH effect, it does not appear to have acted via restricting nutrient availability.

In onions grown on Site 3, the P concentration in the YML at mid-growth decreased more or less uniformly from 0.69 % dry weight on 0 t RMG/ha to 0.34 % dry weight on 180 t RMG/ha. The yield also decreased by 15 t/ha between 0 and 135 t RMG/ha. However, the differences in plant growth at harvest were much less than those observed earlier in the life of the crop. That is, some 'catch-up' in growth was observed. In the early stages of growth, the size of the plants decreased uniformly at increasing level of RMG. Some chlorosis was also seen on the tips of the young leaves, which have been attributed to high salt concentrations in the RMG.

Site 2. The carrots on Site 2 did not show any yield response to level of RMG and no growth differences were observed between treatments. Leaf P concentration was not measured. Uniformly high Bic-P levels are the most likely explanation for this.

The reduction in availability of P to plants on RMG-amended soil was no doubt a result of the increased P buffering capacity of RMG-amended soil which decreased the amount of P in solution at any one time (McPharlin *et al.* 1994a). The magnitude of the required increase in P applications necessary for 99 % of maximum yield will vary between crops. In most cases, the farmer will be economically worse off after the first crop on amended soil as P inputs are increased without any return in increased yield.

The 'catch up' in growth observed on Site 1 and in the onions on Site 3 may have been caused by one or more of several factors. Firstly, the soluble carbonates and the gypsum in the RMG may have been leached from the aggregates of RMG into the surrounding soil and caused the precipitation of dicalcium phosphate (DCP). DCP is sparingly soluble in water and is stable in calcareous soils for at least several months (Greenland and Hayes 1981). It may have acted as a slow release P fertiliser, increasing P availability later in the crop's growth. However, this would also be expected to have occurred on Sites 4 and 5, but as there was no 'catch up' in growth observed on these sites this explanation is unlikely. Secondly, the high EC levels

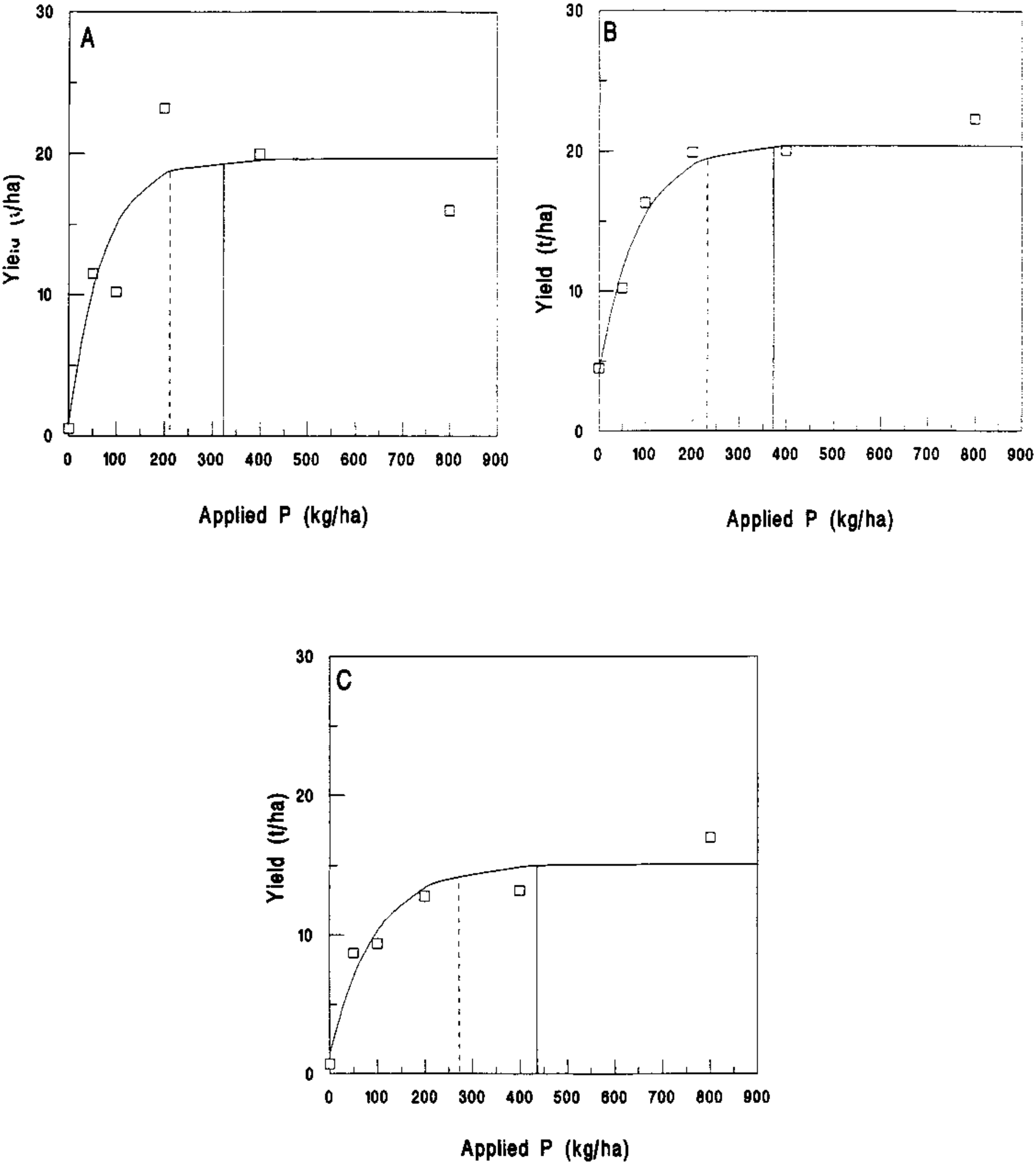

Fig. 10. Total yield of cauliflowers (c.v. 'Arfak') curds vs. level of currently-applied P on (a) 0, (b) 60 and (c) 120 t RMG/ha.

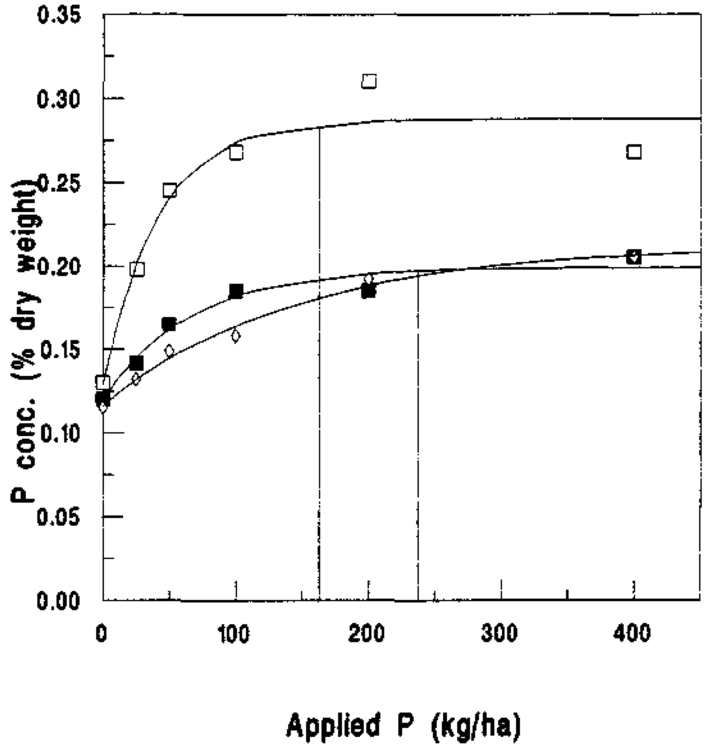

Fig. 11. Concentration of phosphorus (P) in the petiole of the youngest mature leaf of potatoes sampled 11 weeks after planting vs. level of currently-applied P on 0 (□), 60 (■) and 120 (◇) t RMG/ha.

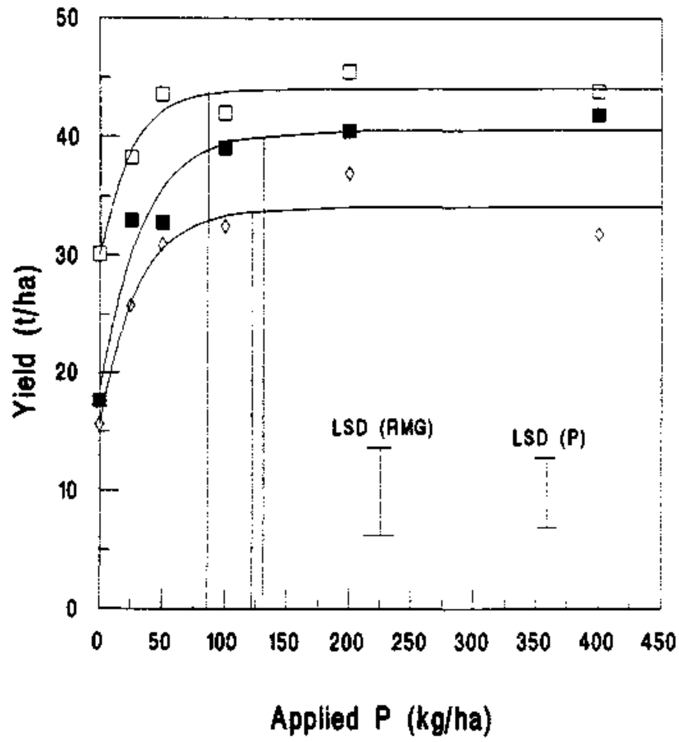

Fig. 12. Total yield of potato tubers (c.v. 'Delaware') vs. level of currently-applied P on 0 (□), 60 (■) and 120 (◇) t RMG/ha.

immediately after RMG amendment may have interfered with P uptake, as hypothesised by Barrow (1982) and Ward (1983). As the salts were leached, so the P became more available. Thirdly, Sites 1 and 3 both received significant quantities of post-planting P applied in small quantities regularly, and in soluble form. This would have created a constant pool of P in soil solution which was immediately available to the plants and which would have overcome the initial P deficiency on amended soil.

This has implications for the management of crops grown on RMG-amended soil. Currently, commercial crops on these poor soils are supplied with most of their P requirement via post-planting applications. Amendment with RMG clearly confers no management advantage in this situation. Adding RMG to the soil requires a change in management practice from this system to a system where all P is added pre-planting, in order to allow soil-testing to be used.

Plant response to residual P

The response of crops to residual P was tested on Site 4, where the growth of cauliflowers was examined. Maximum yield decreased significantly as the level of RMG increased. The difference in fitted maximum yields between 0 and 120 t RMG/ha was 9 t/ha (Fig. 13). As a result, the level of residual Bic-P required for 99 % of maximum yield decreased from 54 ug/g on 0 and 60 t RMG/ha and 37 ug/g on 120 t RMG/ha. For 95 % they were 36, 37 and 28 ug/g. The values observed on unamended soil are in agreement with values observed previously for cauliflowers on a yellow Karrakatta sand (40 ug/g for 95 % and 55 ug/g for 99 %) (McPharlin unpublished data).

Concentration of P in the WL at heading showed a similar response to RMG as that on currently-applied P, except that it maximised at higher levels of applied P. At 800 kg P/ha the P concentration was the same on all levels of RMG. At lower levels of applied P, the P concentration showed a trend to decrease with increasing level of RMG. Maximum P concentration was the same on residual P as it was on currently-applied P (Fig. 14).

The question of whether RMG increases the residual value of applied P is complicated by the reduction in maximum yield on 120 t RMG/ha. However, the downward trend in leaf P with increasing level of RMG at low P levels suggests that P was still less available on amended soil than on unamended soil. This is not surprising as the difference in Bic-P between unamended and amended soil was only a few units (Table 7). The reason for the decrease in yield on 120 t RMG/ha is not clear. It was obviously not due to reduced P availability and no other nutrient deficiencies could be found. The soil pH was approximately 8.5 on 120 t RMG/ha which is above the pH range preferred by cauliflowers of 6.0 to 7.5 (Mattaboni 1990). This may have caused

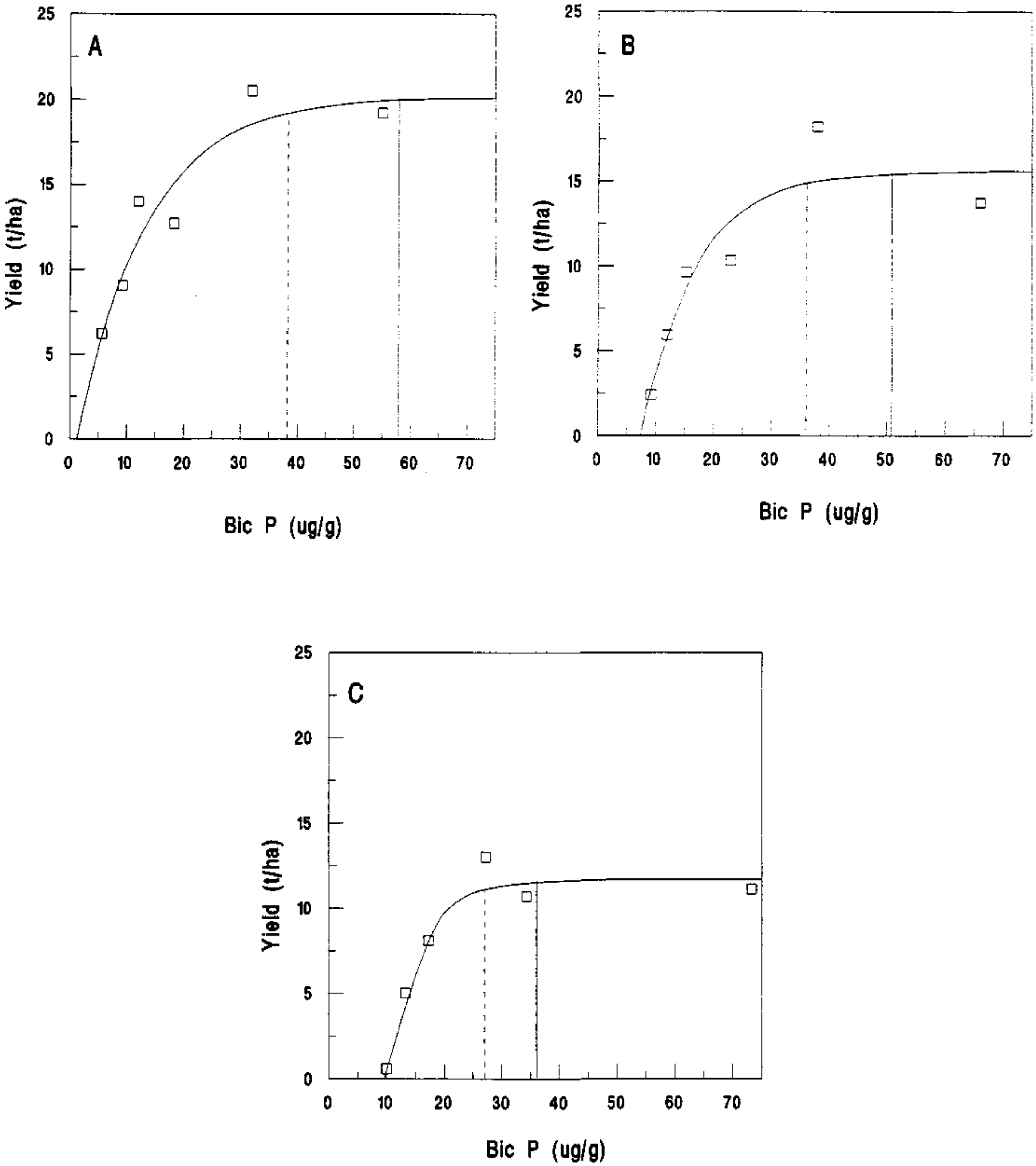

Fig. 13. Total yield of cauliflowers (c.v. 'Arfak') curds vs. concentration of bicarbonate extractable (soil test) P at planting on (a) 0, (b) 60 and (c) 120 t RMG/ha.

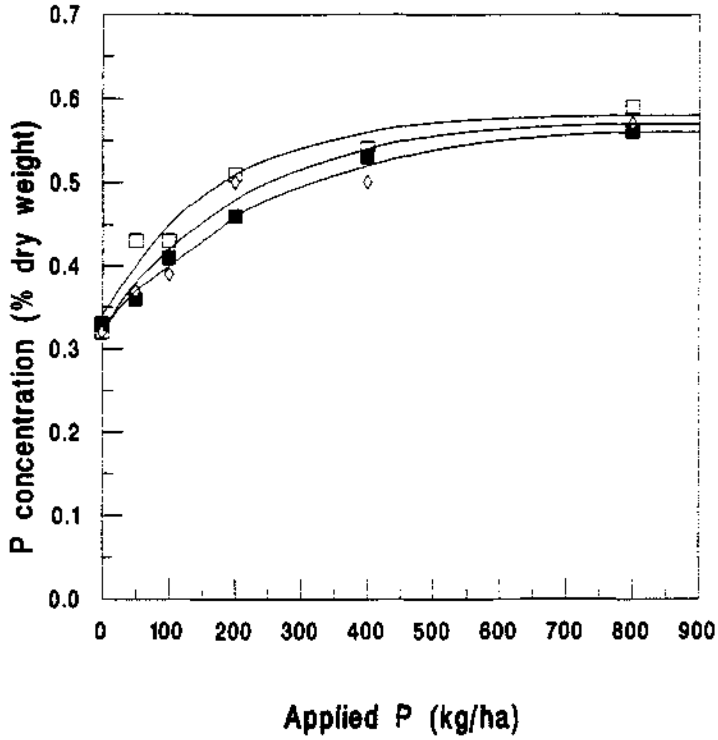

Fig. 14. Concentration of phosphorus (P) in the wrapper leaf of cauliflowers (c.v. 'Arfak') sampled at buttoning vs. level of P applied 4 months before planting on 0 (□), 60 (■) and 120 (◇) t RMG/ha.

some growth reduction in a way not related to nutrient availability, however, it must be noted that the pH was the same on both current and residual P while the growth reduction was only observed on residual P.

Other nutrients

In the column study, the leaching of NH_4-N was observed to decrease at RMG levels of greater than 16 t/ha. At 64 t RMG/ha or more, the leaching of NH_4-N was reduced by 40 to 50 %. There was no effect on the leaching of NO_3-N (graph not shown). The amount of extractable NH_4-N in the top 20 cm of soil also increased on amended soil, from 6 µg/g at up to 8 t RMG/ha to 16 µg/g at 128 and 256 t RMG/ha (data not shown). This was equivalent to approximately 45 kg N/ha on 128 and 256 t RMG/ha.

The availability of N and other nutrients to plants was determined on Chinese cabbage (trial no. 92PE5) and cabbage (trial no. 93PE30) on Site 1, lettuce (trial no. 92MD37) and cauliflowers (trial no. 93MD8) on Site 4 and potatoes on Site 5 (trial no. 93MD9). Table 11 shows the effect of RMG on the concentrations of a range of nutrients in the leaf tissue of the crops measured at some stage during growth. Of all the nutrients whose concentrations were determined, only N, Zn and Cl showed exactly the same response in all cases. The concentration of N was not affected by RMG, despite the observed reduction in N leaching in the column study. This could probably be attributed to the fact that N fertilisers were applied regularly in soluble form throughout the life of the crop. Concentrations of Zn and Cl always decreased on amended soil. This can be attributed to the higher pH of amended soil. The adsorption of Zn onto sesqui-oxides is stronger at high pH (James and Barrow 1981) while Cl uptake is increased at low pH (Mengel and Kirkby 1987). The increased amount of sesqui-oxides in amended soil would also have increased Zn adsorption.

Several other nutrients showed a fairly consistent trend one way or the other. For example, Na and Ca concentrations increased with level of RMG on all but one occasion. This was no doubt because of the addition of these elements to the soil in RMG. The Ca would be supplied by the gypsum and the Na in the red mud itself (Barrow 1982). The concentration of Mn decreased on two occasions, and in both cases it decreased to a deficient level. As a result growers must be careful to increase the Mn supplied to crops on amended soil. Ward (1983) also observed a decrease in the concentration of Mn in clover and medics which he attributed to the increased soil pH reducing its availability.

All other nutrients were either generally unaffected by RMG or the effect of RMG was inconsistent. The effect of RMG on Mo concentration was variable although it was observed to decrease with increasing RMG on two occasions. This is unusual as

Table 11. The effect of RMG on the concentrations of nutrients in the leaf tissue of several crops at some stage during growth. Those nutrients whose concentrations were decreased to a deficient level are indicated (*).

Site	Crop	Tissue	Stage	N	K	Mg	Na	B	Zn	Cu	Mn	Ca	S	Mo	Fe	Cl
1	†Chinese cabbage	‡WL	Heading	-	↑	nd††	nd	nd	nd	nd	nd	nd	nd	nd	nd	nd
1	Cabbage	WL	Heading	-	↑?	↓	↓	↓?	↓	↓	↓*	↑	↑	↑?	-	nd
4	Lettuce	WL	Heading	-	↓*	-	↑	↑	↓	-	↓*	-	-	-	-	↓*
4	Cauliflowers	WL	Buttoning	-	↓	-	↑	-	↓	-	-	↑	-	↓	-	nd
5	†Potatoes	‡PYML	‡‡11 weeks	-	↓	↑	↑	↓	↓	-	-	↑	-	↓	↑	↓

† No standards for adequate nutrient concentrations available for this crop or stage of growth.

‡ Indicates Wrapper Leaf and Petiole of Youngest Mature Leaf.

? True relationship unclear because of insufficient data points.

†† not determined.

‡‡ 11 weeks after planting.

Mo availability usually increases with pH, as was observed by Ward (1983). The increased amount of sesqui-oxides in amended soil may have increased the adsorption of Mo, making it less available. It is not clear why this effect would have been dominant in the cauliflower and potato crops and not on any other site.

Plant disease

Site 5 was inoculated with Powdery Scab (*Spongospera subterranea* (Wallr.) Lagerh. f. sp. *subterranea* Tomlinson) in order to observe the response of the disease in potatoes. Symptoms were not well developed on the tubers from inoculated soil in that it was often difficult to distinguish early symptoms of scab from sunken lenticels. As a result, assessment was difficult.

Even so, there was some indication that the incidence of Powdery scab decreased between amended and unamended soil. On unamended soil, 90 % of tubers sampled had symptoms of Powdery scab compared with 66 % and 57 % observed on 60 and 120 t RMG/ha. However, one sample of 120 t RMG/ha had an incidence of Powdery scab almost as severe as 0 t RMG/ha. Any reduction in the incidence of Powdery scab on RMG-amended soil may have been because of the higher pH of the amended soil being outside the preferred pH range of the causative organism (from 4.7 to 7.6; Hooker 1981). However, the effect of pH on Powdery scab is disputed (Brenchley and Wilcox 1979). An alternative explanation is that the sulphur in the RMG may have been the cause as sulphur has been reported to reduce the intensity of scabbing (Hooker 1981).

Rhizoctonia canker (*Rhizoctonia solani* Kuhn) was also observed. The incidence of Rhizoctonia decreased between 60 and 120 t RMG/ha. That is, only 30 % of tubers sampled from 120 t RMG/ha had symptoms, compared with 71 and 74 % on 0 and 60 t RMG/ha. No satisfactory explanation for the reduced incidence of this disease could be found.

Heavy metals

Table 12 shows the effect of RMG on concentrations of metals in the edible portions of the crops tested. Metals were measured by ICP-MS in all cases except in the carrots where they were measured by flame spectro-photometry.

Table 12. The effect of increasing rates of red mud/gypsum (RMG) on the concentrations of metals in a range of crops grown on RMG-amended soil. An upwards arrow indicates that RMG increased the concentration of the metal and a downwards arrow indicates that RMG decreased the concentration of the metal.

Metal	Carrots†	Onions‡	Chinese‡ cabbage	Lettuce‡	Cauli-‡ flowers	Potatoes‡
As	nd*		-	↑	↑	↓
Se	nd	-	-	↑	↑	-
Sb	nd	-	-	-	↑	-
Cr	-	-	-	↑	-	-
Ba	nd	↓	↓	-	-	↑
Pb	↓	-	-	-	-	-
Cd	↓	↓	-	-	-	-
Ni	-	-	↓	-	-	-
Cu	nd	nd	↓	-	-	-
Co	nd	-	-	-	-	-
Mo	nd	-	-	-	-	-
Hg	nd	nd	nd	-	nd	-

† Concentrations determined by flame spectrophotometry.

‡ Concentrations determined by ICP-MS.

* Not determined

The legal limits for As, Se and Sb concentrations are 1.0, 1.0 and 1.5 mg/kg fresh weight (NFA 1992). Even though the concentrations of these metals increased with level of RMG in many vegetables, the means were always less than 4 % of the legal limits (Table 13).

Table 13. Mean concentrations of As, Se and Sb (mg/kg fresh weight) on the highest level of red mud/gypsum (RMG) tested, in the edible portions of those crops where the concentrations of the metals were observed to increase with level of RMG.

Crop	Highest RMG (t/ha)	Metal As	Metal Se	Metal Sb
Onions†	180	0.018	-	-
Chinese cabbage†	240	0.012	0.034	<0.002
Lettuce‡	480	0.07	0.017	-
Cauliflowers††	120	0.07	0.025	-

† Fresh weight concentrations based on an assumed dry matter content of 10 %.

‡ Fresh weight concentrations based on a calculated dry matter content of 7 %.

†† Fresh weight concentrations based on a calculated dry matter content of 8 %.

While concentrations of Cr only increased consistently in lettuce, there were some high concentrations observed in Chinese cabbage on amended soil. These were 0.64, 0.23, 0.56 and 0.26 mg/kg fresh weight. There is no legal limit for Cr concentrations in food, but the highest concentration observed in Chinese cabbage is no higher than the 'background' concentrations of Cr observed in a wide range of vegetable crops grown on a sandy loam soil (Keefer *et al.* 1986). It was also comparable to the mean concentration of Cr observed in potatoes on both unamended and amended soil (1.22 mg/kg fresh weight). The highest mean concentration of Cr in lettuce was 0.07 mg/kg fresh weight.

Some high concentrations of Pb were observed in lettuce, cauliflowers and potatoes at 120 t RMG/ha or more. These were close to or greater than the legal limit of 2.0 mg/kg fresh weight (NFA 1992) (Table 14). However, they were also 10 times greater than the overall means and the means were always less than one-eighth of the legal limit. Lead is a common environmental contaminant (Mengel and Kirkby 1987), so contamination of several samples is to be expected. Considering that the overall means are much lower than the legal limit, it is reasonable to conclude that Pb concentrations will not be a problem in these vegetables when grown on RMG-amended soil.

The highest mean concentration of Ba observed in potatoes was 0.44 mg/kg fresh weight. This is approximately equal to the overall mean concentration of Ba in lettuce (0.38 mg/kg fresh weight), where there was no response to level of RMG.

Table 14. Mean and high concentrations of Pb in lettuce, cauliflowers and potatoes grown on a yellow Karrakatta sand. Means are averaged over several levels of red mud/gypsum (RMG).

	Lettuce	Cauliflowers	Potatoes
Mean	0.22	0.20	0.19
High value	2.31	2.85	1.34

Based on these data, it is reasonable to conclude that RMG applications, even up to 480 t RMG/ha, are safe for use with the vegetable crops tested, at least in the short term. However, it remains debatable how many different crops need to be tested before it can be decided that RMG is safe for all vegetable crops. Those tested here cover a range of botanical groups (Umbelliferae, Amaryllidaceae, Brassicaceae, Compositae and Solanaceae) and a range of different plant parts (leaf or head, flower, root, bulb and tuber). That all of these crop types showed acceptable concentrations of these metals is encouraging but, if RMG application is to be used commercially, some of the remaining crop groups should also be tested. These include : Chenopidaceae (e.g. Spinach and beet) and Cucurbitaceae (e.g. cucumber and rockmelons).

It is difficult to determine precisely which factors caused the changes in metal availability on RMG-amended soil. Factors that may have been involved are : soil concentration of the metal, the amount of iron and aluminium oxides in the soil and the soil pH. The increased pH of amended soil was probably the reason for the increased availability of As (O'Neill 1990), Se (Fleming 1980) and Sb (Jones *et al.* 1990) which caused plant concentrations to be higher than on unamended soil. The uptake of As has been observed to be less in potatoes than in carrots and lettuce (O'Neill 1990). This may be related to the observed decrease in As concentration in potatoes as level of RMG increased. Clearly another factor was operating in this crop to make its response different from those of the other crops, but whether it was a soil factor or a plant factor is unknown.

The reduced availability of Pb, Cd, Ni and Cu on amended soil can be explained by either the increased pH of the soil or its increased content of iron and aluminium oxides (Basta and Tabatabai 1992; Davies 1990; Alloway 1990; McGrath and Smith 1990) or both. An increased soil pH can also reduce the plant availability of Co (Smith 1990), Mo (Fleming 1980) and Hg (Steinnes 1990).

This raises the question of whether a long term decline in soil pH on amended soil will increase the availabilities of these metals and if their concentrations would subsequently reach violative levels. As discussed previously in this report, there are no long term data on the effect of RMG on the soil pH under a horticultural management system.

Radiation

Soil radiation. Soil radiation was measured in the column study (Table 15). Between 16 and 256 t RMG/ha, the activity concentration of Th-232 increased from 0.01 to 0.08 Bq/g. This represented the major component of the soil radiation. All activity concentrations of Ra-226 and K-40 were below detectable limits. The annual radiation dose for 100 % occupancy was 0.51 mSv/year at the highest level of RMG, based on the concentration of Th-232 (Table 15). If it is assumed that normal levels of Th-232 in the soil contribute about 0.2 mSv/year, then the annual radiation dose from 256 t RMG/ha exceeded background by about 0.3 mSv/year. This is well below the legal limit of 1 mSv/year above background and is much less than levels commonly found in the Darling Range (3 to 6 mSv/year) or on some beaches containing mineral sands, such as Minninup beach (12 mSv/year) (Toussaint 1988).

Table 15. Activity concentrations (Bq/g) and annual radiation doses (mSv/year) from several radio-nuclides in a Joel sand amended with red mud/gypsum (RMG). The results are means of three replicates.

RMG (t/ha)	^{232}Th (Bq/g)	^{232}Th (mSv/yr)
0	<MDL*	<MDL
8	<MDL	<MDL
16	0.01	0.07
32	0.02	0.10
64	0.02	0.15
128	0.05	0.35
256	0.08	0.51

* Less than minimum detectable limits.

There were also no significant levels of Radon (^{222}Rn) daughters in the vicinity of the RMG/soil samples within a glasshouse over 24 hours. Concentrations of Ra-228, Th-232 and K-40 in the leachate were all below detectable limits. Detectable quantities of Ra-226 were observed in several samples of leachate, including those from treatments where no RMG was added. There was no significant difference between RMG levels (Table 16).

Table 16. Activity concentration Ra-226 (mBq/L) in leachate collected from a Joel sand amended with red mud/gypsum (RMG). Leachate was collected after 408 mm of water was applied over 12 days. The results are means of three replicates.

RMG (t/ha)	^{226}Ra (mBq/L)
0	24.3
32	27.0
64	34.0
128	20.0
256	18.7
Significance	N.S.

The risk of radiation exposure from soil amended with RMG up to 256 t/ha therefore appears to be minimal.

Plant radiation. No U-238, Th-228, Ra-226, Ra-228 or Pb-210 was detectable in the edible portions of cauliflowers, potatoes or cabbage. There were detectable concentrations of all of these radio-nuclides in lettuce, except U-238, although concentrations did not change significantly with level of RMG (data not shown).

There were detectable levels of K-40 and Cs-137 (from nuclear fallout, not associated with RMG) in all crops, but again there was no consistent increase in their activity concentrations with increasing level of RMG. In fact, the concentration of Cs-137 in cabbages was observed to fall as the level of RMG increased (data not shown).

The annual radiation dose from the consumption of vegetables grown on RMG-amended soil was estimated using an assumed consumption rate of 100 kg/year for each type of vegetable (Table 17). Most of the dose comes from Pb-210 and Th-228. The magnitude of the doses are comparable with the estimated world-wide averages for internal exposures from natural radio-nuclides in food (UNSCEAR 1993).

Table 17. Estimated annual doses (uSv) from the consumption of vegetables grown on RMG-amended soils (based on a consumption of 100 kg of each vegetable per year).

Radionuclide	Lettuce	Cabbage	Potato	Cauliflower
^{210}Pb	40	11	57	20
^{226}Ra	7	2	9	3
^{228}Ra	11	2	6	4
^{228}Th	70	13	38	27
^{137}Cs	0.4	1.2	0.4	0.1
^{40}K	35	14	45	30

There is therefore little or no risk of excessive radiation doses resulting from the consumption of these vegetables grown on RMG-amended soil. As for heavy metals, it must be determined how wide a range of vegetables must be tested before it can be concluded that RMG-amendment is generally safe. The crops tested include both head or leaf vegetables and a tuberous vegetable. If RMG is to be used commercially, it would be wise to test the radio-nuclide concentrations in carrots, as this is the most widely grown crop on the Swan Coastal Plain. Some crops where the harvested product is the fruit, such as tomato, should also be tested.

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