

# Phosphorus fertilizer requirements for macadamia.

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Final report to :-

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## Summary

Field trials, glasshouse experiments and laboratory analyses were conducted to investigate the phosphorus requirement of macadamia. The validity of various soil phosphorus tests and leaf analysis for diagnosing the soil phosphorus status in relation to macadamia growth and production was also studied.

Leaf phosphorus analysis of seedlings provided a reasonable indicator of the plant's requirement for phosphorus. However, phosphorus analysis of leaf material from the field trial sites (mature trees) showed that leaf phosphorus was relatively insensitive to the levels of available phosphorus in the soil and that the use of leaf analysis as the sole diagnostic index is fraught with uncertainty.

In pot trials optimum seedling growth was obtained when extractable soil phosphorus (soil test) levels were 50, 23 and 29 mg P/kg soil for Colwell, Olsen and Bray 1 extractable phosphorus, respectively. The Colwell soil phosphorus test is widely used in Australia and the results from the field trials suggest that optimum nut-in-shell yield would be obtained at a soil test level (Colwell method) of around 60-70 mg P/kg soil in the surface 10cm.

The field trials also demonstrated that when soil test (Colwell method) levels exceed 150-200 mg P/kg a yield reduction is likely. A limited survey of macadamia plantations in Queensland has shown that some have soil test levels (Colwell method) of more than 200 mg P/kg. In some instances soil test levels are greater than 300 mg P/kg as a result of repeated applications of phosphorus fertilizer.

The results of this work demonstrate that high levels of soil phosphorus can reduce yields and it is suggested that many producers can reduce operating costs by not applying phosphorus fertilizer when soil test levels (bicarbonate extractable phosphorus, Colwell method) are above about 70 mg/kg in the surface 10cm. At lower soil test levels (Colwell method), phosphorus fertilizer application is likely to result in increased nut-in-shell yield but has little effect of the quality index of percent first grade kernels.

At only one of the three field trial sites was nut-in-shell yield significantly increased by the application of phosphorus. This yield increase occurred within one year of fertilizer application, and showed that, where soil phosphorus levels are deficient, a relatively small cash outlay for phosphorus fertilizer could result in a substantial increase in cash receipts. Results from this project have provided macadamia producers, consultants and extension officers with an additional diagnostic tool in deciding whether or not phosphorus fertilizer is required. Prior to this study, soil tests had not been calibrated against macadamia yield response.

It is suggested that producers, consultants and extension officers use all of the aids available (plant symptoms, plant analysis, soil tests) to arrive at a fertilizer recommendation. However, it must be remembered that interpretations of plant and soil tests are suspect unless the tests have been properly calibrated.

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## 1. INTRODUCTION

The phosphorus fertilizer requirements of macadamias have not been thoroughly investigated. Some industry growers have suggested that macadamias have a high phosphorus requirement and that application rates of phosphorus should be increased. Stock (1987) suggested that current soil and leaf standards for phosphorus were too low to give maximum growth and productivity. However this belief has not been thoroughly tested by experimentation. Newett (1987) presented experimental data indicating a significant yield response to phosphorus. However, the phosphorus was applied as rates of 'Superking' (containing phosphorus, sulphur and calcium) and no mention is made of whether the treatments were 'balanced' for sulphur and calcium. Thus there is a possibility that the yield response recorded may have been due to factors other than phosphorus alone. The yield improvements from 'Superking' only lasted one year.

Identification of the need to apply phosphorus fertilizer can be accomplished by using both soil and leaf analysis. Although survey work has provided a guide to appropriate leaf levels of phosphorus there has been no soil test calibration for macadamias. Soil tests currently used for phosphorus in Australia have not been calibrated with responses in macadamia. A belief (Stock, 1987) that the optimum soil test value lies above 100 mg P/kg soil (acid extractable or bicarbonate extractable) also requires investigation.

Work in Hawaii (e.g. Cooil *et al.* 1966, Shigeura *et al.* 1974) has demonstrated that additions of phosphate to lava land or high phosphate fixing soils can result in macadamia yield increases. The availability of 'native' phosphorus on these soils would be very low indeed. A similar situation exists in many of the red loam (Krasnozem) soils which support macadamia production in northern New South Wales and Queensland. However, macadamias (native to rainforest areas in southern Queensland) might reasonably be expected to have some adaption to low phosphorus soils. This report describes the results of a project which aimed to provide producers with a clearer picture of the macadamias' requirement for phosphorus fertilizer.

The objectives were to determine the effects of phosphorus application on (a) macadamia seedling growth and (b) growth, yield and quality of nuts of mature, commercial macadamia trees, in soils with a range of phosphorus levels. The usefulness of various soil phosphorus tests for diagnosing the soil phosphorus status in relation to macadamia growth and production was also investigated.

## 2. INVESTIGATIVE APPROACH

In addition to plant analysis, soil test results are used by macadamia producers, consultants and extension officers as a basis for fertilizer recommendations. However, the prerequisite for correct interpretation of any soil test is that the test has been calibrated against the yield response for the crop of interest.

To provide a sound basis for interpretation of soil tests a large number of field trials (usually 15 to 50 sites), in which the yield response to fertilizer application is measured,

need to be conducted (Rayment 1985, Moody and Bruce 1988). These yield responses are then related to soil test values to find the best soil test and establish optimum soil test levels for the nutrient in question. This calibration procedure is time consuming and very costly and for a tree species such as macadamia, for which a response to fertilizer application may take a considerable time, is not really practical. We therefore approached the aim of the project by calibrating soil tests for seedling macadamias grown in a range of soils in a glasshouse and conducting field trials (3 sites only) in established macadamia plantations.

## 2.1 Glasshouse trials with seedling macadamia

Glasshouse experiments using seedling macadamias were conducted to examine (i) seedling growth response to added phosphorus (P) in a range of soils, (ii) relationships between seedling response to added P and extractable soil P levels using a range of extractants and (iii) the relationship between seedling growth and leaf P levels.

### 2.1.1 Soil Analyses

Twelve soils (4 from established macadamia plantations) were collected (0-10 cm depth) from sites in south east Queensland to give a range of soil P levels. The soils were air dried, sieved < 5 mm and a subsample ground < 2 mm for laboratory analysis.

Each soil was analysed for pH (1:5 soil:water), organic carbon (uncorrected Walkley - Black value), effective cation exchange capacity (Bruce and Rayment 1982), particle size distribution (Day 1956), 0.005 M CaCl<sub>2</sub> extractable P (Moody *et al.* 1983), and NH<sub>4</sub>F/HCl extractable P (Bray and Kurtz 1945). Phosphorus extractable with 0.5M NaHCO<sub>3</sub> was determined using both the Colwell (1963) procedure (1:100 soil:solution, 16 h extraction) and the Olsen and Summers (1982) procedure (1:20 soil:solution, 30 min extraction). Soil phosphorus buffer capacity was determined from P sorption curves (Moody *et al.* 1983) as the amount of P sorbed between solution P concentrations of 0.25 and 0.35 mg P/L.

The concentration of phosphorus in the soil solution was determined by wetting each soil to field capacity (10 kPa matric suction moisture content), allowing the moist soil to equilibrate for 4 days, extracting the soil solution by centrifugation and measuring the solution P concentration using the auto analyser procedure of Warrell and Moody (1984).

### 2.1.2 Glasshouse experimentation

The glasshouse trials consisted of two experiments conducted simultaneously. For each glasshouse trial, air dry soil (weights ranging from 4 to 5.5 kg) was placed in polyethylene lined pots (20cm diameter) and basal nutrients (in solution form) applied to the soil at rates (mg element/pot) equivalent to 800, 250, 100, 50, 8, 16, 6, 1, 3 and 24 for N, K, S, Mg, Cu, Zn, Mn, Mo, B and Fe, respectively. Calcium (130 mg/pot), as gypsum, was then dry mixed through the soil in each pot.

In Experiment 1, a randomised block design was used with 10 soils (soils 1 to 10), 2 levels of phosphorus (nil and added P) and 6 replications of each treatment. The rate of added P, designed to result in soil solution P concentrations of 100 to 200  $\mu\text{g P/L}$  in each soil, was calculated from P sorption curves (Moody et al. 1988) conducted in the laboratory. This rate varied from soil to soil and ranged from 188 to 1884 mg P/pot.

In Experiment 2, eight rates of phosphorus (0, 40, 80, 160, 320, 640, 1280, and 2560 mg P/pot) were applied to each of two soils (soils 11 and 12) with 6 replications of each rate in a completely randomised design. These soils were selected as they had been sampled from sites of phosphorus rate field trials on established macadamia plantations (see below).

In both experiments, monocalcium phosphate was dry mixed with the potted soil to give the appropriate rate of P addition. The soils were then wet to the field capacity (10 kPa matric suction) moisture content and equilibrated for 2 weeks. Macadamia (*Macadamia integrifolia* Maiden and Betche) seedlings which had been pregerminated in washed sand for 6 weeks were then transplanted (1 seedling/pot) into the potted soil.

Pots were watered with deionised water by weight to the 10 kPa matric suction moisture content once every 2 days for the first 6 weeks of growth and thereafter once each day. Additional nitrogen (160 mg N/pot) as  $\text{NH}_4\text{NO}_3$  in solution form) was applied to the potted soil after growth periods of 8 and 16 weeks to ensure that nitrogen was not limiting.

Seedlings were grown for 23 weeks in both experiments and then the stem and leaves removed, washed in deionised water, dried at 60°C and weighed. In Experiment 1 relative whole top dry matter growth was calculated as growth in the nil P treatment as a percentage of growth with added P. In Experiment 2 relative growth for each level of added P was obtained by expressing the growth as a percentage of the maximum observed growth for that soil. With the exception of the added P treatment in Experiment 1, the root material was recovered from the soil, washed and the proteoid roots separated from the root system. Roots and proteoid roots were dried at 60°C and weighed. Leaf material from each pot was ground, digested (Kjeldahl) and analysed for P and N (auto analyser). Separate subsamples of leaf material from Experiment 2 were analysed for Cu, Zn, Mn and Fe (X-ray fluorescence).

After recovery of roots from the soil in Experiment 2 separate subsamples were used to determine the soil solution P concentration and extractable phosphorus using the procedures previously described.

## 2.2 Field trials in established macadamia plantations

Three field trials were established for this project. Some time was spent in attempting to find sites with very low soil phosphorus levels and to which no P fertilizer had been applied. However, since most plantation managers had applied P at some time, it was not possible to find sites without any added P. On the basis of soil P tests, three sites, with relatively low soil P levels, were selected. The location and soil properties of these sites are given in Table 1.

**Table 1** Soil properties at three field trial sites in established macadamia plantations.

Site Name	Location	Clay (%)	Organic carbon (%)	ECEC <sup>A</sup> (mmol(+)/100g)	pH <sup>B</sup>	Soil solution P <sup>C</sup> (µgP/L)	Bicarbonate extr. P <sup>D</sup> (mg/kg)	Bray 1 extr. P (mg/kg)
El Briale	Pomona	8	0.7	2	5.6	46	33	17
Haylock	Kin Kin	52	2.2	9	5.9	44	62	25
Como Park	Eulama	11	0.8	2	5.8	68	38	24

- <sup>A</sup> Effective cation exchange capacity (nutrient holding capacity)  
<sup>B</sup> 1:5 soil:water  
<sup>C</sup> Phosphorus concentration in soil solution extracted from soil wet to field capacity  
<sup>D</sup> Colwell (1963) method

At each site, treatments consisted of 7 rates of P with 4 replicates of each rate as single tree plots. The P was applied to the soil surface as triple superphosphate (19.4% P) and the rates applied at each site are given in Table 2. Gypsum (calcium sulphate) was applied to each plot to balance the calcium and sulphur in the superphosphate so that P was the only varying factor across treatments. Treatments were applied to 5m x 5m single tree plots, centred on the tree, on the 20th and 21st November 1989. To achieve uniform distribution of the added fertilizer, each plot was subdivided into 1m x 1m subplots and appropriate amounts of the fertilizer uniformly applied to the subplot through a sieving device.

Table 2 Rates of phosphorus application at each field trial site.

Site	Rate of applied P			
	kg P/ha	g P/tree <sup>A</sup>	g P/m <sup>2</sup>	kg TSP <sup>B</sup> /tree <sup>A</sup>
El Briale and Como Park	0	0	0	0
	10	25	1	0.13
	20	50	2	0.25
	40	100	4	0.52
	80	200	8	1.03
	160	400	16	2.06
	320	800	32	4.12
Haylock	0	0	0	0
	15	37.5	1.5	0.19
	30	75	3	0.39
	60	150	6	0.77
	120	300	12	1.55
	240	600	24	3.09
	480	1200	48	6.18

<sup>A</sup> applied to a 5m x 5m area centred on the tree  
<sup>B</sup> triple superphosphate

The management of trees followed normal practice for the respective plantations, excepting that animal manures and phosphorus containing fertilizers were excluded.

Tree growth was assessed by trunk girth measurements once each year. Nuts were harvested each year (2-3 harvests during the April-August period) and the yields (nut-in-shell and kernel) and quality (% first grade) recorded.

Soil samples were collected in November each year. At each sampling, 5 cores (8 cm diameter) were taken from the 0-5cm and 5-10 cm depths in each plot and the respective depth intervals bulked. Soil samples were air dried, sieved <2 mm and analysed for extractable P using the tests previously described (see section 2.1.1).

Leaf samples (mature leaves from the 2nd whorl of current season's growth) were collected from each tree in late October and analysed for phosphorus. Leaf samples from selected treatments were also analysed for nitrogen, potassium, sulphur, calcium, magnesium, copper, zinc, manganese and iron.



Table 3 Soil phosphorus parameters and other selected properties of the soils (glasshouse Experiments 1 and 2).

Soil	Great Soil Group <sup>A</sup>	Soil soln P ( $\mu\text{g/L}$ )	0.005 M $\text{CaCl}_2$ P ( $\mu\text{g/kg}$ )	0.5 M $\text{NaHCO}_3$ extr. P (mg/kg)		$\text{NH}_4\text{F}/\text{HCl}$ P (mg/kg <sup>-1</sup> )	pH (1:5 water)	Organic C (%)	ECEC (mmol(+)/100g)	Clay (%)	P buffer capacity (mg P kg <sup>-1</sup> /0.10 mg PL <sup>-1</sup> )
				Colwell	Olsen						
1	Krasnozem	13	64	44	13	8	7.1	1.3	17	57	23
2	Yellow podzolic	7	15	1	<1	1	5.9	0.6	2	8	5
3	Human gley	7	19	4	1	2	5.6	1.9	9	35	16
4	Krasnozem	13	14	3	1	1	6.3	0.8	11	51	20
5	Red podzolic	665	2075	135	50	163	5.8	1.7	6	10	-4
6	Krasnozem	350	650	150	51	172	6.4	1.4	7	15	23
7	Krasnozem	17	39	3	1	2	6.2	4.0	12	38	31
8	Red podzolic	25	42	10	5	8	5.5	2.8	6	15	19
9	Yellow podzolic	20	46	13	5	11	5.4	1.6	3	13	15
10	Alluvial	255	1038	37	16	19	7.9	1.5	21	19	5
11	NSG <sup>B</sup>	44	122	31	16	26	5.9	2.2	9	52	22
12	Red Earth	68	117	48	10	24	5.8	0.8	2	11	12

<sup>A</sup> Stace *et al.* (1968)

<sup>B</sup> no suitable group

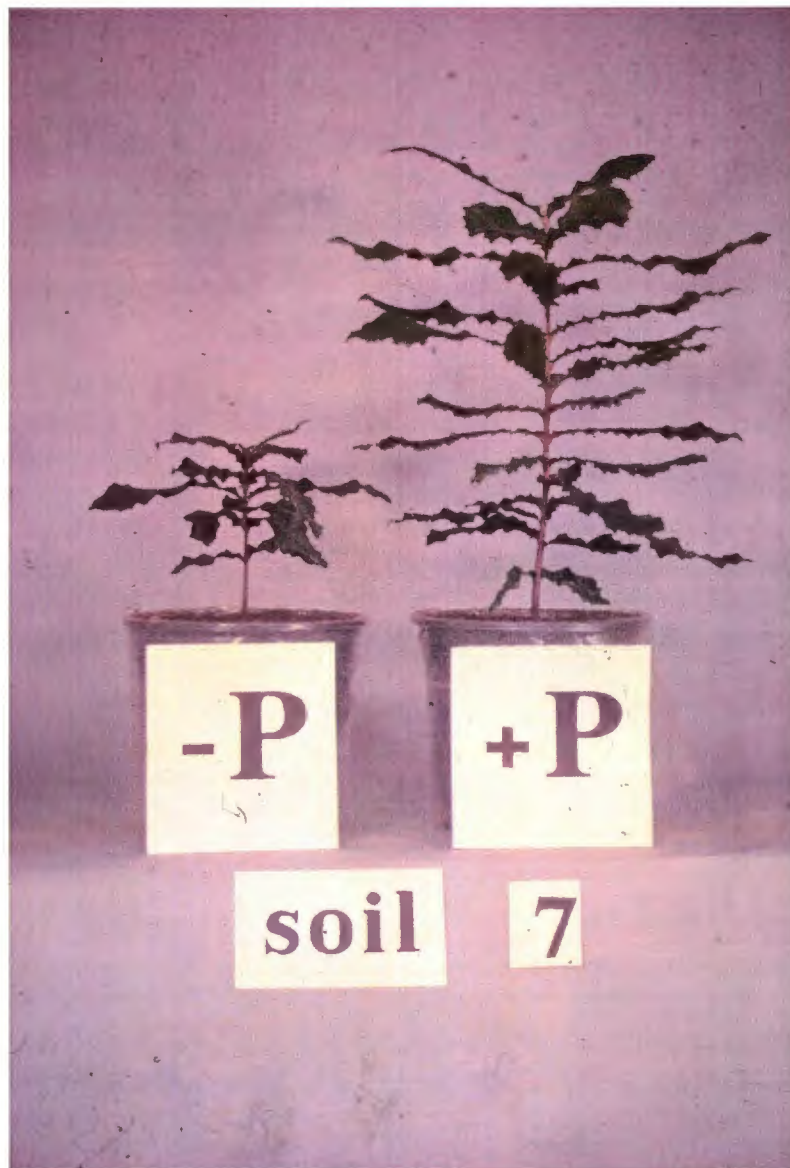


Plate 1. Effect of applied phosphorus on macadamia seedling growth in a phosphorus deficient soil.

### 3. RESULTS AND DISCUSSION

#### 3.1 Effect of phosphorus application on seedling growth

The phosphorus status and selected properties of each soil are given in Table 3 which shows that many of the soils contained low levels of extractable P. Soils 5 and 6 were sampled from established macadamia plantations that had received frequent applications of P fertilizer. Although soils 11 and 12 did not have the lowest soil P test values (Table 3) they were used for the rate trials (Experiment 2) as they had been sampled from the sites of P rate field trials on established macadamia plantations.

##### 3.1.1 Whole top growth

In Experiment 1 the application of P significantly ( $P < 0.05$ ) increased whole top dry matter growth in 5 of the 10 soils (Table 4). Plate 1 shows the effect of phosphorus on seedling growth in a soil with a low phosphorus status. The greater than two fold increase in seedling growth recorded in some soils emphasises the benefit of applying P fertilizer when the requirement for P exists. However, there are difficulties in extrapolating these results (Table 4) to older trees. The relatively large seed of macadamia may contribute P to the seedling's P requirement and it is possible that more responses to added P would have been obtained with a longer growth period. On the other hand the internal P requirement of a plant usually declines with plant age (Jones 1968, Moody and Edwards 1978, Johansen *et al.* 1980).

**Table 4** Dry matter growth of tops (with and without added P), leaf P concentrations in macadamia seedlings (nil P treatment), and proteoid root growth in the nil P treatment of each of 10 soils (glasshouse Experiment 1)

Soil	Dry matter top growth (g/pot)		Leaf P concentration (%)	Relative proteoid root growth (%)
	Nil P	Added P		
1	9.78	10.53	0.10	14
2	6.83	11.53*	0.05	18
3	6.61	14.55*	0.03	15
4	8.06	8.03	0.05	27
5	11.01	10.67	0.13	<1
6	7.94	9.16	0.10	8
7	9.34	24.52*	0.03	14
8	7.50	10.30*	0.06	27
9	7.83	11.66*	0.08	28
10	9.50	10.79	0.08	12

\* Significantly ( $P < 0.05$ ) different from nil P treatment.

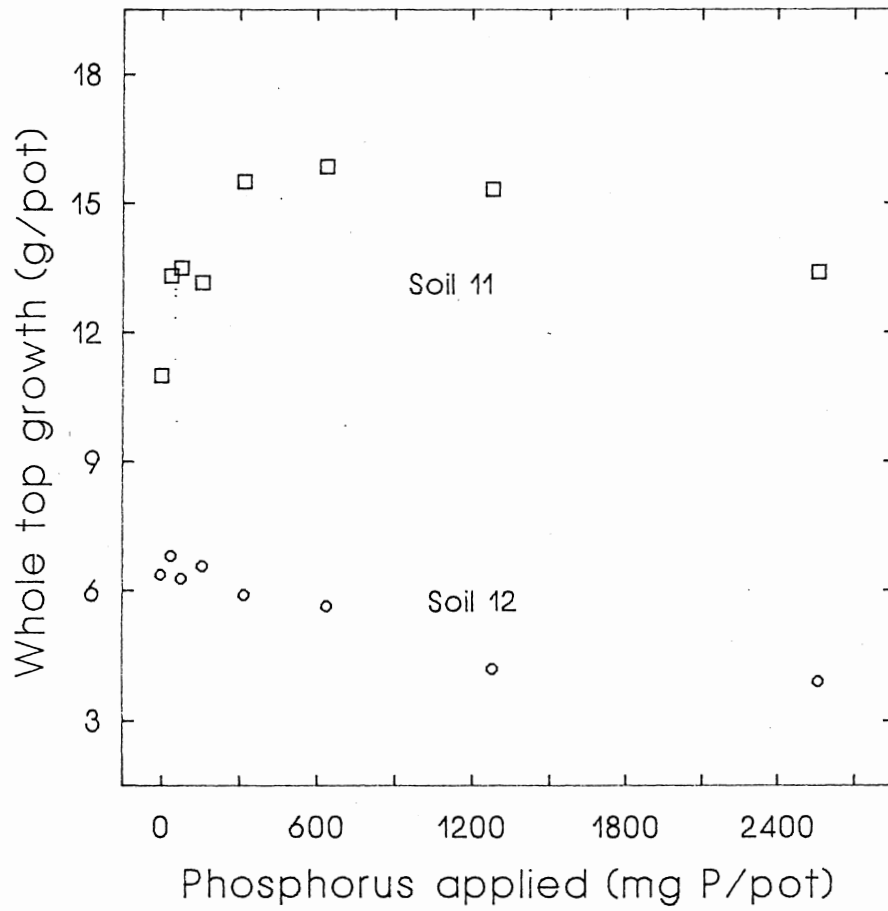


Figure 1. The effect of rate of applied phosphorus on whole top macadamia seedling growth in two soils (glasshouse Experiment 2).

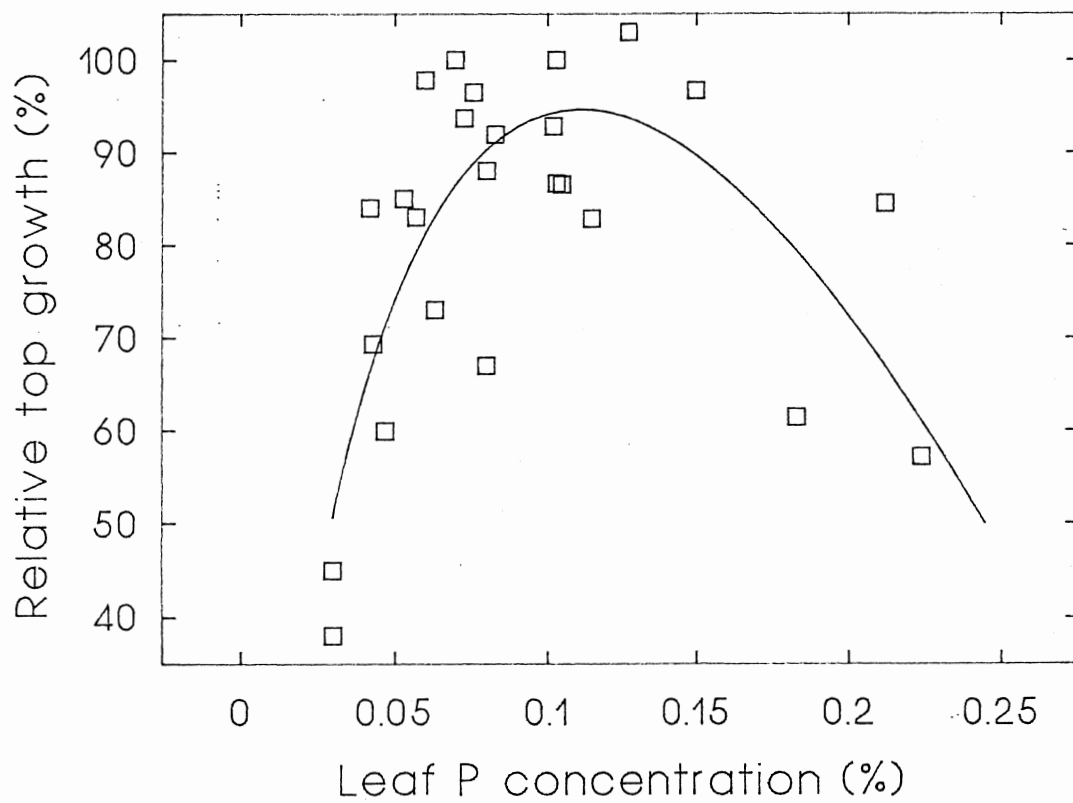


Figure 2. The relationship between relative whole top macadamia seedling growth and leaf phosphorus concentration (data from glasshouse Experiments 1 and 2 combined).

The effect of rate of applied P on the growth of plant tops grown in soils 11 and 12 (Experiment 2) is shown in Figure 1. Seedling growth was significantly ( $P < 0.05$ ) increased by P application in soil 11 whereas in the sandy loam (soil 12) application of  $\geq 1280$  mg P/pot resulted in seedling growth significantly ( $P < 0.05$ ) lower than the maximum. The highest P rate added to soil 11 also resulted in growth significantly below the maximum. Plants grown with high rates of added P,  $\geq 1280$  mg P/pot in soil 11 and  $\geq 320$  mg P/pot in soil 12, exhibited symptoms of chlorosis (pale yellow-green) on the younger leaves. Plates 2 and 3 show the effect of various rates of phosphorus on seedling growth. In addition to an obvious growth increase with added phosphorus, chlorosis (pale yellow/green) (Plate 2) and reduced growth (Plate 3) is evident on seedlings treated with high phosphorus rates. Leaf levels of Cu, Zn and Mn in these plants (data not presented) were in the adequate to high range (Robinson 1986). Although leaf levels of iron (Fe) were  $\geq 25$  mg/kg, the leaf Fe/P ratio was  $\leq 0.07$  in plants with growth significantly below the optimum suggesting that Fe deficiency (Hue and Nakamura 1988) may have been partially responsible for the reduced growth. Iron chlorosis induced by high rates of P application to macadamias has been previously documented (Hue *et al.* 1988, Hue and Nakamura 1988).

Phosphorus concentrations in leaf material from nil P treatments (Experiment 1) were all  $\leq 0.13$  % P and leaf samples from responsive soils contained  $\leq 0.08$  % P (Table 4). The relationship between relative growth of plant tops (growth in nil P treatment as a percentage of growth with added P) and leaf P concentration is shown in Figure 2. A quadratic function ( $R^2 = 0.60$ ) fitted to this relationship (which includes data from both Experiments 1 and 2) resulted in a critical leaf P concentration of 0.08% corresponding to a relative growth of 90%.

Based on survey work (unpublished data), Robinson (1986) suggested that leaf P levels of around 0.08 to 0.1 % P would be adequate for macadamia. Results obtained in this study, which has defined the critical leaf P concentration using classical means (Ulrich 1952), indicate that levels similar to those suggested by Robinson (1986) apply to seedling macadamia. Work in Hawaii (Cooil *et al.* 1966, Hue *et al.* 1988) has also indicated that about 0.1% P in leaves is an optimum P concentration. A critical leaf P concentration of around 0.1% established for macadamia is typical of critical leaf P concentrations of other native Australian species (Bell 1985).

Leaf P concentrations (Experiment 2) above 0.15% P were associated with reduced growth (Figure 2). Although a P-induced Fe deficiency may have been responsible for this reduced growth (discussed previously), most plants grown at high rates of added P in soil 12 also exhibited necrosis on the tips of older leaves and the existence of P toxicity *per se* cannot be discounted. Grundon (1972) has shown that other Proteaceae (*Banksia* and *Hakea* species) are susceptible to phosphorus toxicity.

### 3.1.2 Proteoid root growth

Although both proteoid root weight and non-proteoid root weight varied from soil to soil in Experiment 1, there was no relationship between proteoid root weight and either the weight of non-proteoid roots or top growth (data not shown). This indicates that the

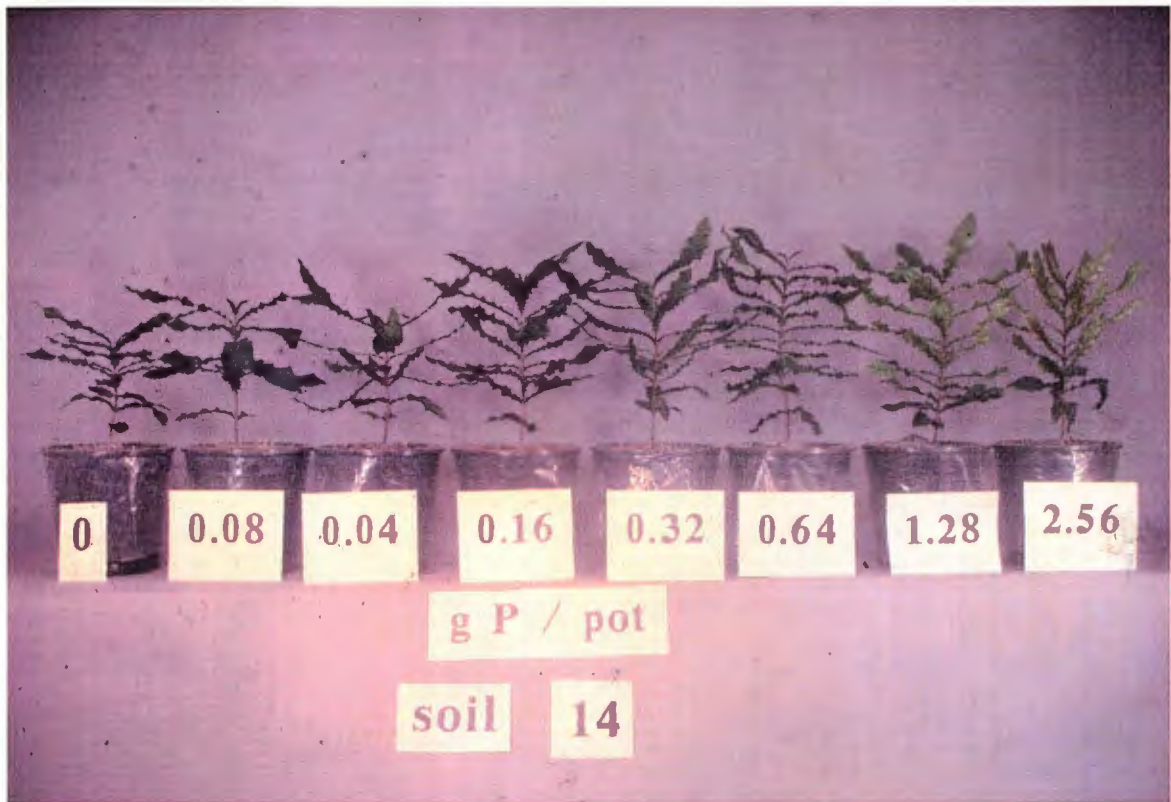


Plate 2. Effect of various rates of added phosphorus on macadamia seedling growth (soil 11, Experiment 2).

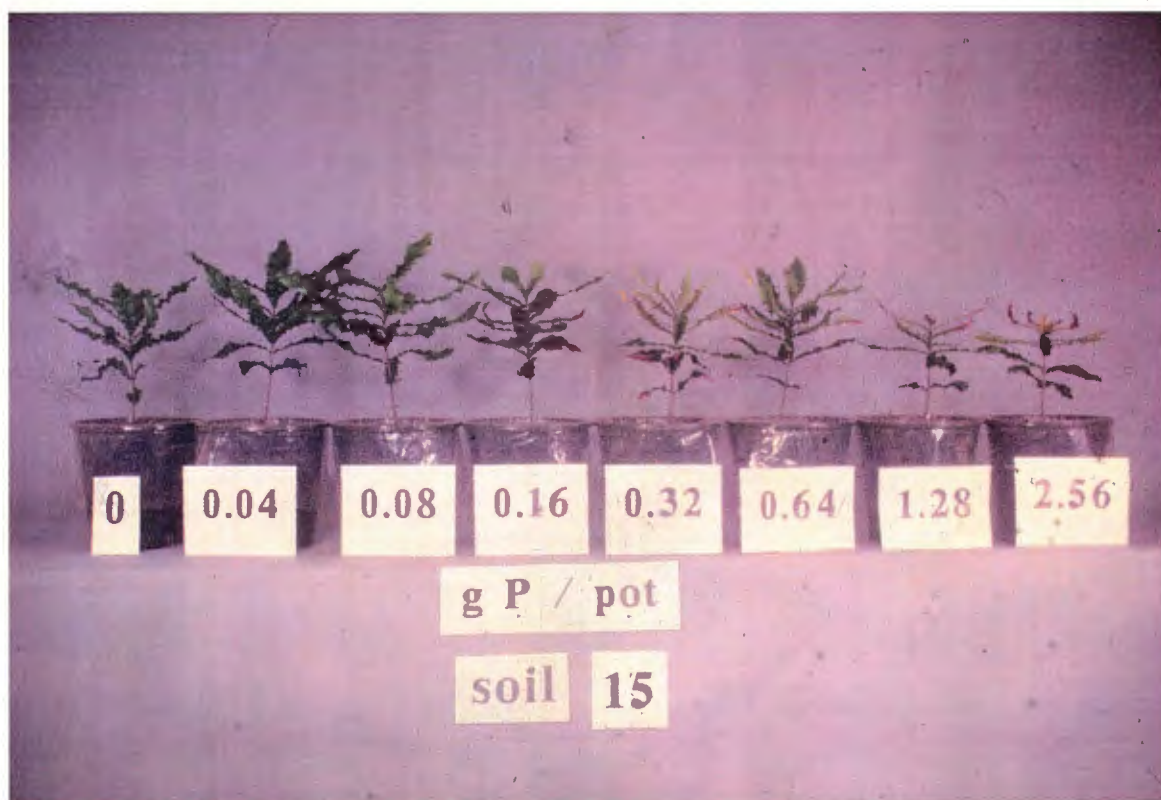


Plate 3. Effect of various rates of added phosphorus on macadamia seedling growth (soil 12, Experiment 2).



extent of proteoid root development is not necessarily dependent on the extent of root development in seedling macadamias. Lamont (1972) also observed that relative proteoid root production was not related to either total root weight or top weight in *Hakea* species. Because differences in root weights between soils may be due to differences in soil physical properties in addition to differing P status, the proteoid root data was expressed on a relative (percentage) basis. The proportion of the root system (proteoid plus non-proteoid roots) that was proteoid root in each soil (Experiment 1) is shown in Table 4. In some soils almost one third of the root mass was composed of proteoid roots. Container grown plants of other proteaceae (*Banksia* and *Hakea* species) have developed proteoid roots which accounted for up to 50% of the total root weight (Lamont 1972, Malajczuk and Bowen 1974).

Figures 3 and 4 show the relationships between proteoid root growth (as a % root weight) and selected soil P test values for Experiments 1 and 2, respectively. There is less scatter in the relationship with soil solution P (Figure 3b) compared with the relationship involving bicarbonate extractable P. Relative proteoid root growth data from Experiment 2 were related to both measures of P quantity (Fig 4 a) and P intensity (Fig 4b) with data from both soils lying on the same relationship in each case. Figures 3 and 4 show that above soil solution P levels of about 100  $\mu\text{g P/L}$  there are few proteoid roots.

These relationships (Figures 3 and 4) do not provide any evidence that proteoid root development is a response to low P levels in the soil. However it is clear that high soil P levels will inhibit proteoid root development in macadamias. Although the relationship between relative proteoid root growth (RPRG) and bicarbonate extractable P ( $P_b$ ) across a range of soils was not as good as that between RPRG and soil solution P (Figure 3) it is clear that at  $P_b$  values  $> 100 \text{ mg P/kg}$  there will be little or no proteoid root growth. Applying P to maintain  $P_b > 100 \text{ mg P/kg}$ , as has been suggested by some sections of the industry, would have detrimental effects on proteoid root development. Since proteoid roots are considered to have functions in addition to that of enhancing P uptake (Lamont 1972), the application of excess P fertilizer may have ramifications with respect to tree vigour.

From data obtained in this study little can be said in relation to the effect of high rates of P on existing proteoid roots in established macadamias. However, as Purnell (1960) has suggested that existing proteoid roots may be functional for only about 3 months, heavy P applications may completely eliminate proteoid roots from established macadamia trees. This aspect requires further investigation.

Although P concentrations substantially higher than those found in typical soil solutions were used, Lamont (1972) also demonstrated that high levels of P ( $\geq 6200 \mu\text{g P/L}$ ) in sand culture reduced proteoid root growth in *Hakea prostrata*. Proteoid roots are reported to be caused by non-infecting rhizosphere microorganisms (Malajczuk and Bowen 1977). The mechanism(s) by which high P levels in soil solution inhibit the induction of proteoid roots has yet to be elucidated.

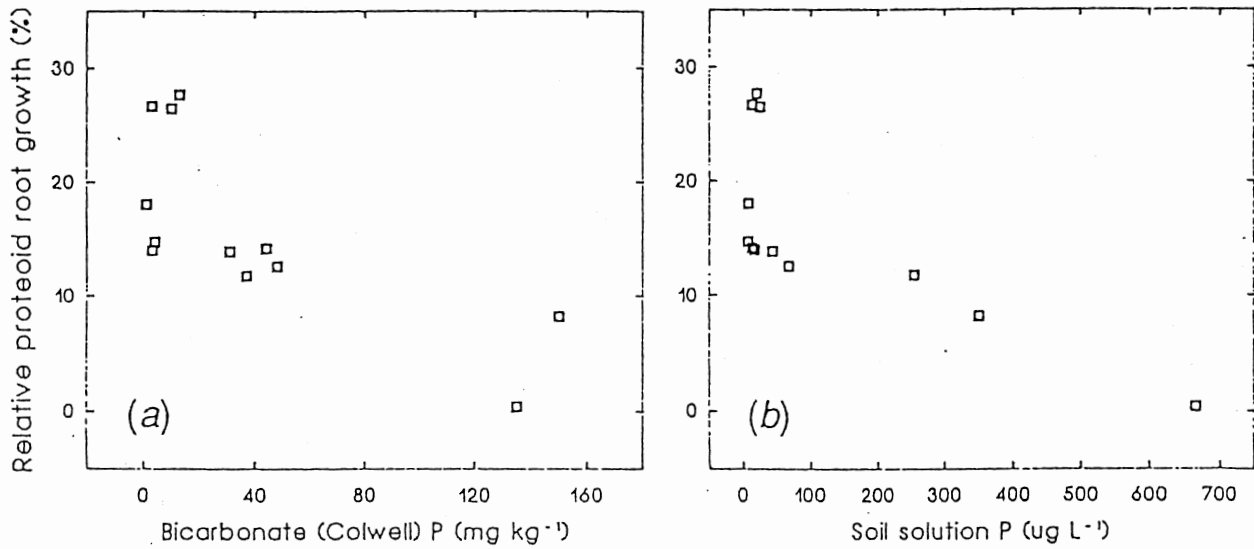


Fig. 3. Relationships between relative proteoid root growth in nil P treatments and (a) 0.5 M NaHCO<sub>3</sub> (Colwell) extractable phosphorus, (b) soil solution phosphorus for 12 soils.

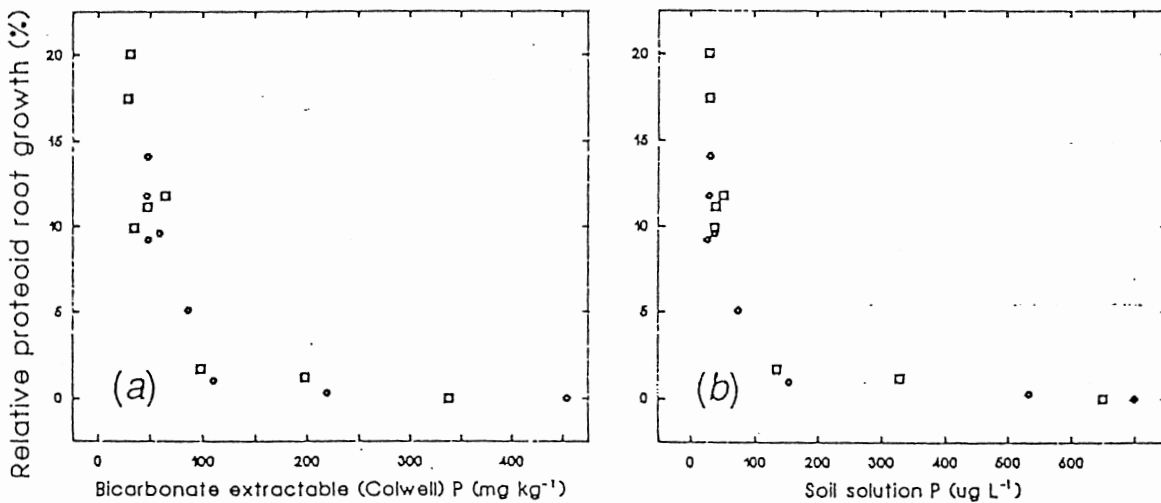


Fig. 4. Relationships between relative proteoid root growth in soils 11 (□) and 12 (○) amended with various rates of applied phosphorus (Experiment 2), and (a) 0.5 M NaHCO<sub>3</sub> (Colwell) extractable phosphorus, (b) soil solution phosphorus.

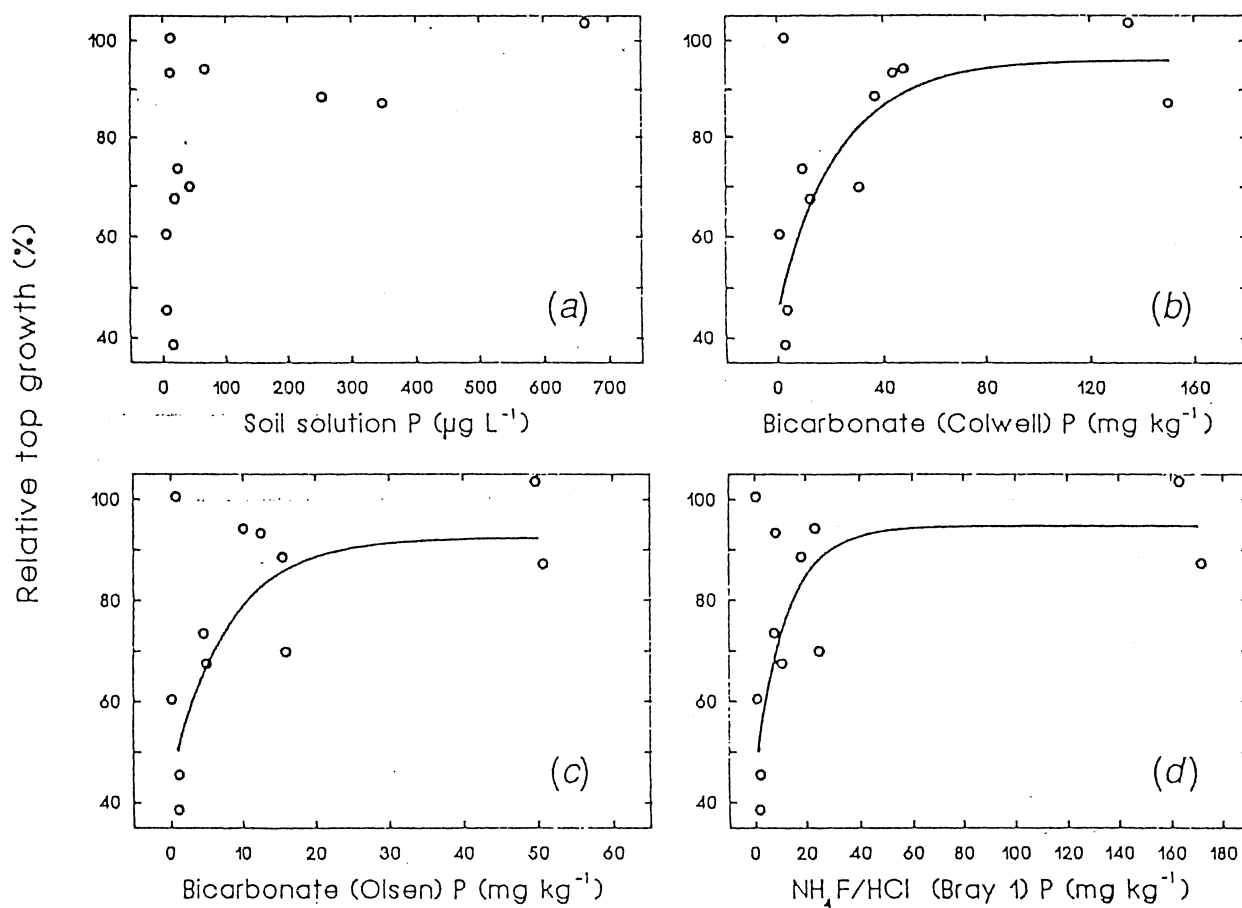


Fig. 5. Relationships between relative whole top macadamia seedling growth and (a) soil solution phosphorus, (b) 0.5 M  $\text{NaHCO}_3$  (Colwell) extractable phosphorus, (c) 0.5 M  $\text{NaHCO}_3$  (Olsen) extractable phosphorus, (d)  $\text{NH}_4\text{F}/\text{HCl}$  (Bray 1) extractable phosphorus. Mitscherlich curves fitted to relationships: (b)  $Y = 96 - 51e^{-0.04x}$ , (c)  $Y = 93 - 47e^{-0.13x}$  and (d)  $Y = 95 - 48e^{-0.08x}$  are shown (see text).

### 3.1.3 Relationships between plant growth and soil phosphorus values

For the purpose of calibrating soil P tests against relative growth, data from Experiments 1 and 2 were combined to give 12 data points. The relationships between relative whole top growth and selected soil test values are given in Figure 5. The relationship between relative growth and 0.005 M CaCl<sub>2</sub> extractable P is not shown as CaCl<sub>2</sub> extractable P was linearly related ( $r^2 = 0.94$ ) to soil solution P.

Of the soil tests regressed against relative whole plant top growth using the Mitscherlich equation, Colwell extractable phosphorus (Figure 5b) was slightly better than Olsen extractable phosphorus (Figure 5c) and Bray extractable phosphorus (Figure 5d) as a predictor of the likelihood of a growth increase with applied phosphorus. However, the relationships shown in Figure 5 indicate that each of the Colwell, Olsen and Bray soil tests could be used to predict whether or not phosphorus fertilizer is required for macadamia seedlings. It was not possible to fit a Mitscherlich equation to the relationship between relative yield and soil solution phosphorus (Figure 5a) because of the large increase in relative growth for a small increase in soil solution phosphorus concentration.

'Critical' soil phosphorus levels required for optimum growth (> 90% of maximum whole plant top growth) were 50, 23 and 29 mg P/kg soil for Colwell, Olsen and Bray 1 extractable phosphorus, respectively. These critical levels enable macadamia producers, consultants and extension officers to interpret soil tests. For example, if a soil is tested for phosphorus using the Colwell method and the level of extractable phosphorus is less than 50 mg P/kg soil, the application of phosphorus fertilizer would be expected to increase seedling growth. If the soil tested at more than 50 mg P/kg then a growth increase with applied phosphorus would not be expected and phosphorus application would not be recommended.

Although soil testing laboratories throughout Australia use a range of test methods for phosphorus, the Colwell, Olsen and Bray methods are widely used.

While the critical Colwell extractable phosphorus value (50 mg/kg) is higher than that reported for some field crops (Dwyer and Moody 1988), it is lower than that suggested by Stock (1987) for macadamia.

Although one soil (soil 4) is an outlier in all relationships (Figure 5) it can be seen that bicarbonate extractable P (in particular Colwell P) results in the best relationships between relative growth and soil P test value. Application of P to soil 4 did not increase seedling growth even though this soil had a low P status (Tables 3 and 4). Plants growing in this soil (nil P treatment) had a high proportion (27%) of the root system as proteoid roots and it is possible that these enhanced P uptake. However this possibility cannot completely account for the lack of a response since other soils (soils 8 and 9) also grew plants with similar proportions of proteoid roots which responded to applied P (Table 4). It appears that the relative growth (100%) for this soil is an overestimate, and therefore this point has been deleted from the regression equations presented in Figure 5.

### 3.2 Field trials in mature plantations

#### 3.2.1 Effect of applied phosphorus on soil test levels

As expected, application of phosphorus increased the level of extractable ('available') phosphorus in the soil (Table 5). Bruce and Rayment (1982) considered that bicarbonate extractable phosphorus levels in soils typically ranged from <10 mg/kg (very low) to around 100 mg/kg and that values >100 mg/kg were very high. Cumming and Elliot (1991) suggested that bicarbonate extractable phosphorus values of around 200-300 mg/kg would result in phosphorus toxicity for most crops. On this basis, the bicarbonate extractable values shown in Table 5 indicate that the treatments resulted in a wide range of values across all three sites.

**Table 5** Effect of applied phosphorus on extractable soil phosphorus (0-5cm) one year after application at each of three field trial sites.

Site	Phosphorus applied (kg/ha)	Soil phosphorus		
		Bicarbonate extractable <sup>A</sup> (mg/kg)		Calcium chloride extractable <sup>B</sup> (µg/kg)
		0-5cm	5-10cm	
El Briale	0	28	34	383
	10	48	43	600
	20	85	53	692
	40	94	65	1500
	80	125	66	1675
	160	181	99	2750
	320	220	98	6065
Haylock	0	62	71	726
	15	72	62	605
	30	76	88	795
	60	97	82	965
	120	153	97	1040
	240	196	116	2256
	480	325	180	4430
Como Park	0	103	63	NP <sup>C</sup>
	10	153	64	NP
	20	177	83	NP
	40	148	70	NP
	80	266	114	NP
	160	256	132	NP
	320	340	194	NP

<sup>A</sup> Colwell (1963) method

<sup>B</sup> Moody et al. (1983) method

<sup>C</sup> Inadvertent application of manure to this site resulted in poor replication of extractable P and results are not presented.

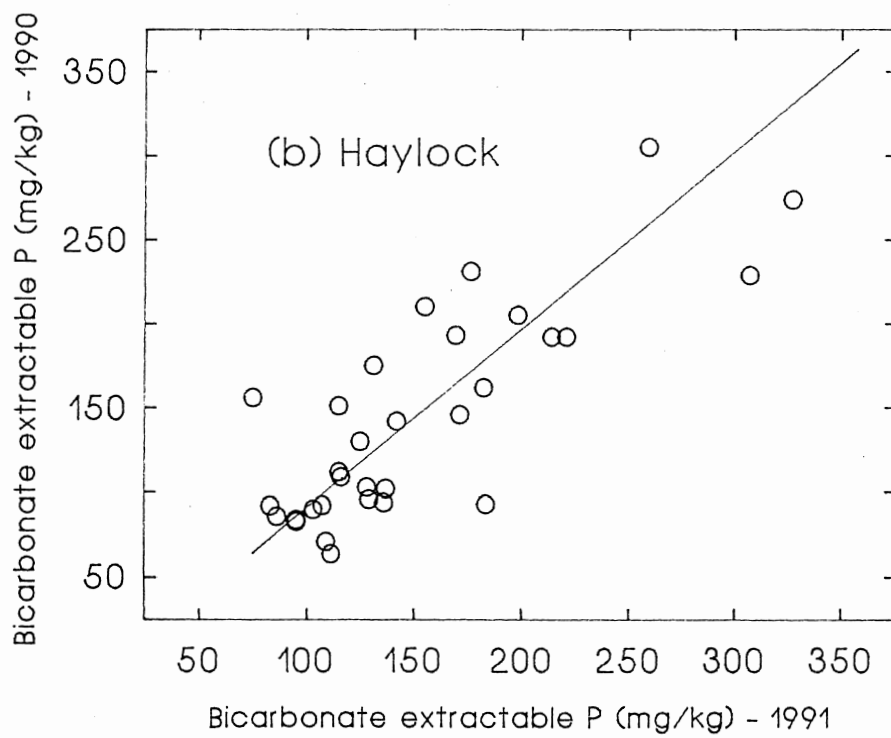
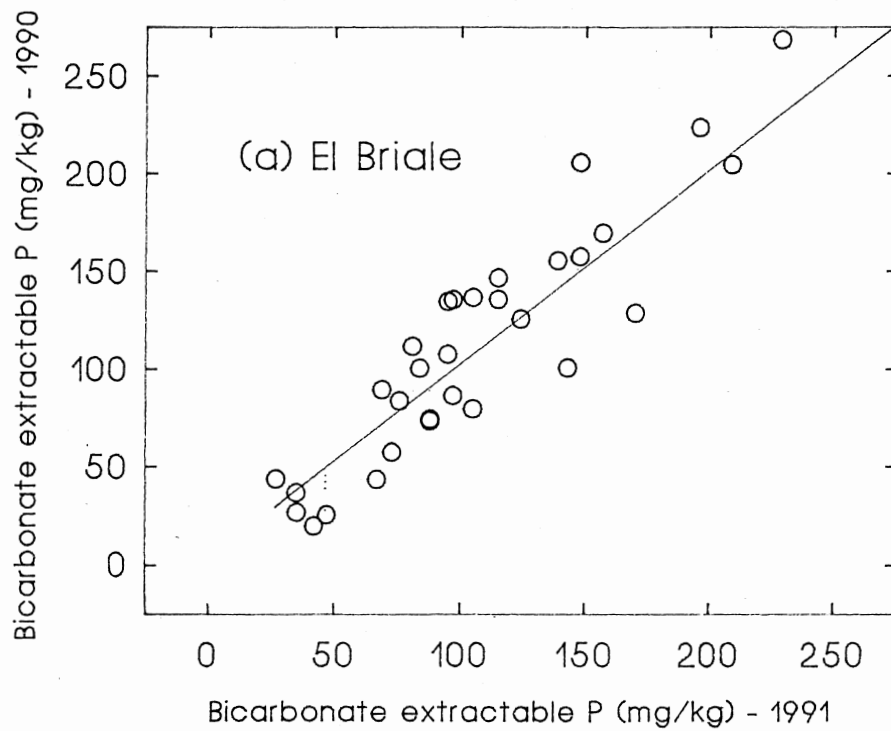


Figure 6. Extractable soil phosphorus levels in 1990 plotted against extractable soil phosphorus level in 1991 for all treatments and replicates.

Calcium chloride extractable phosphorus (Table 5) is a measure of the 'intensity' of soil phosphorus (i.e. an index of the phosphorus in soil solution). Previous studies (e.g. Moody *et al.* 1988) have shown that calcium chloride extractable phosphorus is linearly related to the concentration of phosphorus in soil solution and it is the latter which is immediately available to the plant roots. The values shown in Table 5 indicate that treatments resulted in both a wide range in phosphorus 'intensity' levels and very high levels of phosphorus in soil solution. For example, Moody *et al.* (1990) showed that above a soil test value of 43  $\mu\text{g P/kg}$  (calcium chloride extractable) a soybean crop would be adequately supplied with phosphorus and no phosphorus fertilizer would be required.

The soil test level in the 'no phosphorus' treatment at Como Park (Table 5) was considerably higher than that recorded at this site prior to the application of phosphorus (Table 1). Investigation of this anomalous result revealed that field staff had inadvertently applied fowl manure to the trial site. Despite this, a range of soil test values existed (Table 5) and data were still collected from this site.

There was little change, for a given phosphorus application rate, in extractable phosphorus level from year to year. Figure 6 shows extractable P in samples collected in 1990 plotted against extractable P in samples collected in 1991 for all plots at El Briale and Haylock sites. Regression lines fitted to these plots indicated a 1:1 relationship between soil test values measured in different years.

In these trials the phosphorus was applied to the soil surface and not incorporated. A comparison of extractable P levels for the 0-5cm and 5-10cm depths (Table 5) shows that high rates of phosphorus application increased extractable phosphorus in the 5-10cm depth. The extent to which extractable phosphorus increased depended on soil type, with the sandier soils (El Briale and Como Park) exhibiting the greatest proportional increase in extractable phosphorus in the 5-10cm depth. The small increase in extractable phosphorus (5-10cm depth) at typical rates of applied phosphorus (10-40 kg P/ha) highlights the low mobility of phosphorus in soils. Work currently being undertaken by the NSW Department of Agriculture regarding placement of phosphorus for macadamia is relevant to this phenomena.

### 3.2.2 *Effect of phosphorus on tree growth, yield and quality*

For all site years, average nut-in-shell (NIS) yields were in the range 10 to 25 kg/tree except at El Briale in 1991 where yields were in the range 4 to 10 kg/tree. The low yields at El Briale in 1991 were attributed to poor flowering in that year.

Average NIS yields for each treatment at each site are shown in Table 6. Yields from individual trees (4 replicate trees for each rate of applied phosphorus) were statistically analysed to determine if yield differences were significant. Applying phosphorus fertilizer significantly ( $P=0.05$ ) increased NIS yield at only one site (El Briale). Although the yields at the Haylock site tended to increase with applied phosphorus (Table 6) these differences were not statistically significant ( $P=0.05$ ). Yield responses were obtained within 1 year of applying the phosphorus fertilizer.

**Table 6** Average nut-in-shell yields for various rates of applied phosphorus at each of three field trial sites for the years 1990 to 1992.

Site	Phosphorus applied (kg P/ha)	Average nut-in-shell yield (kg/tree)			
		1990	1991	1992	Total
El Briale	0	13.3	5.7	12.9	31.9
	10	12.3	4.6	11.7	28.6
	20	16.5	8.4	16.9	41.8
	40	18.1	6.9	16.1	41.1
	80	17.1	10.8	17.9	45.8
	160	17.9	4.6	15.6	38.1
	320	14.7	4.4	14.6	33.7
		**	*	*	
Haylock	0	12.7	13.1	10.3	36.1
	15	13.4	15.4	12.6	41.4
	30	14.0	14.6	14.5	43.1
	60	15.3	16.0	15.3	46.6
	120	13.8	15.5	14.7	44.0
	240	13.4	14.2	14.9	42.5
	480	11.1	13.9	14.6	39.6
		NS	NS	NS	
Como Park	0	16.9	14.9	19.5	51.3
	10	15.7	14.9	17.8	48.4
	20	14.4	14.2	18.3	46.9
	40	17.9	13.6	18.0	49.5
	80	15.6	15.2	19.6	50.4
	160	15.0	14.1	18.2	47.3
	320	14.0	17.4	25.5	56.9
		NS	NS	NS	

\*\* Treatment means significantly different (P = 0.01)

\* Treatment means significantly different (P = 0.05)

NS Treatment means not significantly different



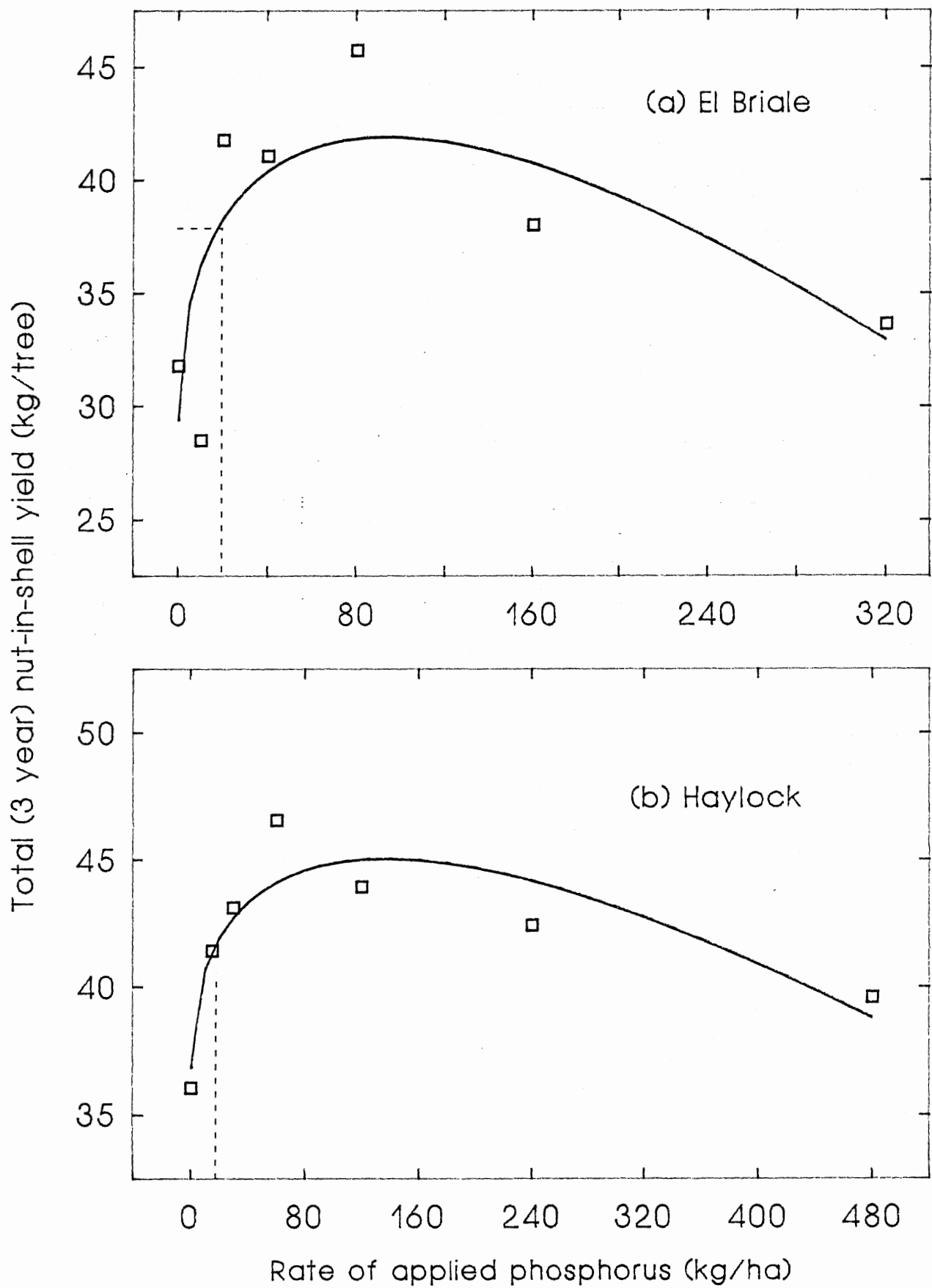


Figure 7. Effect of rate of applied phosphorus on nut-in-shell yield (3 year total) at each of two sites. Curves were statistically fitted to the data.

Figure 7 shows the relationship between total yield (3 year total) and phosphorus applied. Although optimum yield (taken as 90% of maximum yield) was attained at approximately the same rate of phosphorus application at each site (about 20 kg P/ha) (Figure 7), the rate of phosphorus required usually varies from site to site and will depend on both the existing soil phosphorus levels and the capacity of the soil to react with the added phosphorus. For example, the Haylock site had a higher soil clay content than the other sites (Table 1) and would be expected to require more applied phosphorus as the clay adsorbs phosphorus and makes it less available to the plant. However, Table 1 shows that the Haylock site originally had a higher soil test level (bicarbonate extractable) than the El Briale site and therefore less applied phosphorus would be required to reach the 'optimum' level in the soil.

Perhaps the most notable feature of Figure 7 is the trend for reduced yield at high rates of fertilizer application. This is a clear demonstration that excess phosphorus will reduce macadamia yield and is discussed further in section 3.2.4.

Although, for a given treatment, average tree girth increased during the 3 years over which the trial was conducted, there was no significant effect of applied phosphorus on tree girth.

Although the phosphorus treatments at El Briale significantly increased NIS yield, there was no significant ( $P = 0.05$ ) effect of treatment on the proportion (%) of first grade kernels irrespective of year. At El Briale nut quality (% first grade kernels) ranged from 94% to 99% across treatments and years. Similarly, at Como Park the proportion of first grade kernels was not affected by phosphorus treatment. At the Haylock site, in 1992 only, the proportion of first grade kernels was significantly ( $P = 0.05$ ) greater from trees receiving phosphorus fertilizer (96%) compared with that from the control (no applied phosphorus) trees (80%). Since this increased quality only occurred in the third year at only one site it would appear that phosphorus fertilizer does not have a major effect on nut quality.

### *3.2.3 Effect of applied phosphorus on leaf P levels*

Table 7 shows leaf phosphorus concentrations for various rates of applied phosphorus at each site for yearly samplings during the period of the project. The striking feature of these results is the lack of sensitivity of leaf phosphorus to the levels of available phosphorus in the soil. Apart from El Briale (1990 only) there was little difference in leaf phosphorus levels (Table 7) despite the very large differences in levels of available phosphorus in the soil (Table 5). Although the differences in soil levels were maintained from year to year (see section 3.2.1) they were not reflected in leaf phosphorus levels (Table 7).

**Table 7** Leaf phosphorus concentrations for various rates of applied phosphorus at each of three field trial sites.

Site	Phosphorus applied (kg P/ha)	Leaf phosphorus concentration (%)		
		1990	1991	1992
El Briale	0	0.08	0.07	0.06
	10	0.09	0.06	0.06
	20	0.08	0.06	0.06
	40	0.09	0.07	0.06
	80	0.11	0.07	0.07
	160	0.11	0.07	0.07
	320	0.14	0.08	0.08
Haylock	0	0.06	0.05	0.05
	15	0.07	0.05	0.06
	30	0.07	0.06	0.06
	60	0.07	0.06	0.06
	120	0.08	0.06	0.06
	240	0.09	0.06	0.06
	480	0.07	0.06	0.07
Como Park	0	0.07	0.07	0.05
	10	0.07	0.07	0.06
	20	0.07	0.05	0.05
	40	0.06	0.06	0.05
	80	0.07	0.05	0.05
	160	0.08	0.06	0.05
	320	0.10	0.07	0.06

Moreover, across all sites there was no relationship between leaf phosphorus and either relative yield or soil phosphorus level (Figure 8).

Leaf phosphorus concentration in these mature trees was unable to predict the requirement for phosphorus fertilizer. On the basis of current recommendations, Haylock and Como Park sites (with leaf phosphorus levels < 0.07% in untreated plots) would be considered marginal whereas trees at El Briale (0.08%) would be considered to be adequately supplied with phosphorus (Robinson 1986). However, at El Briale, yield was significantly increased by phosphorus application but no yield response was recorded at Haylock or Como Park. This is in contrast to the results from the glasshouse trials (see section 3.1.1) in which leaf phosphorus was a reasonable indicator of seedling growth.

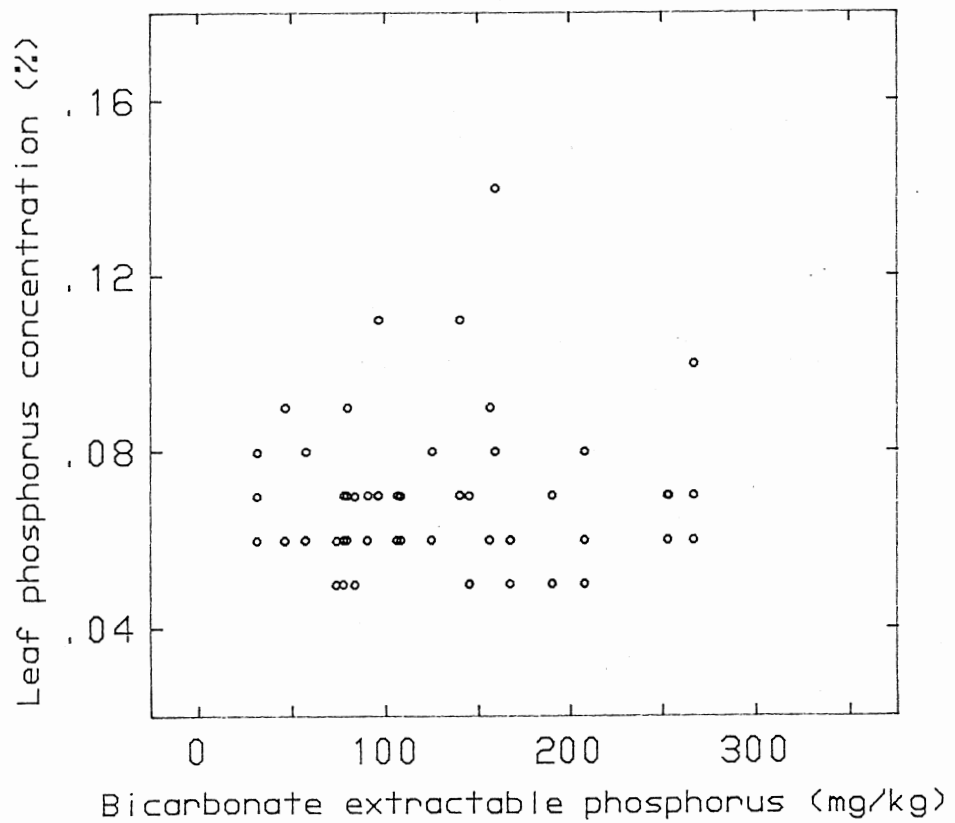
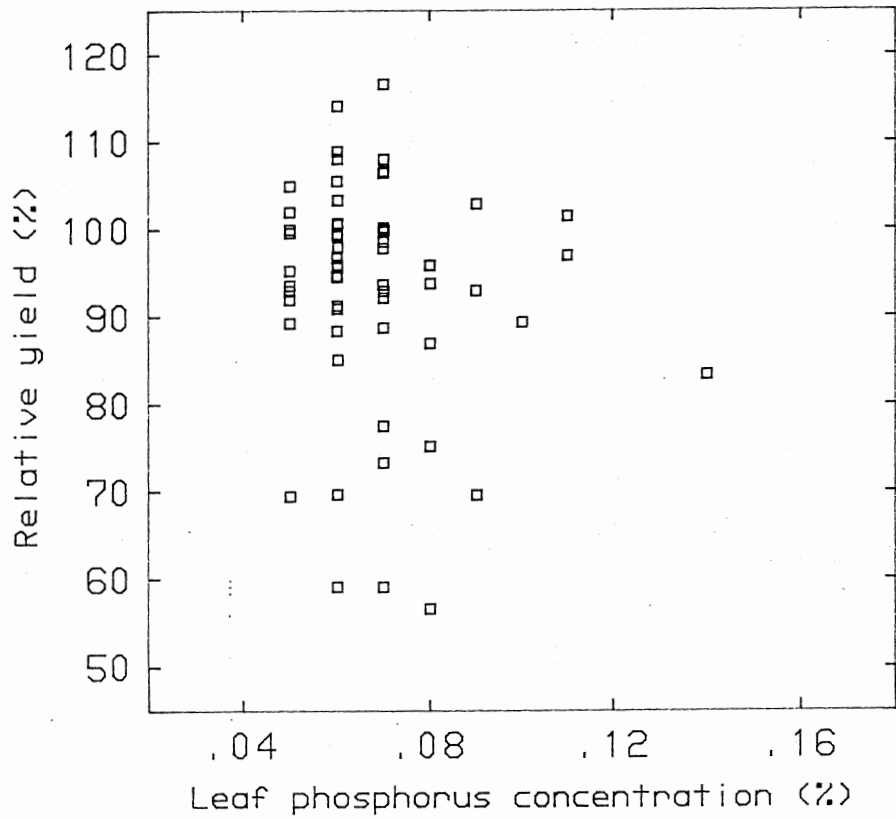


Figure 8. Scatterplots of leaf phosphorus concentration against relative yield and extractable soil phosphorus (Colwell method) for all sites and years.

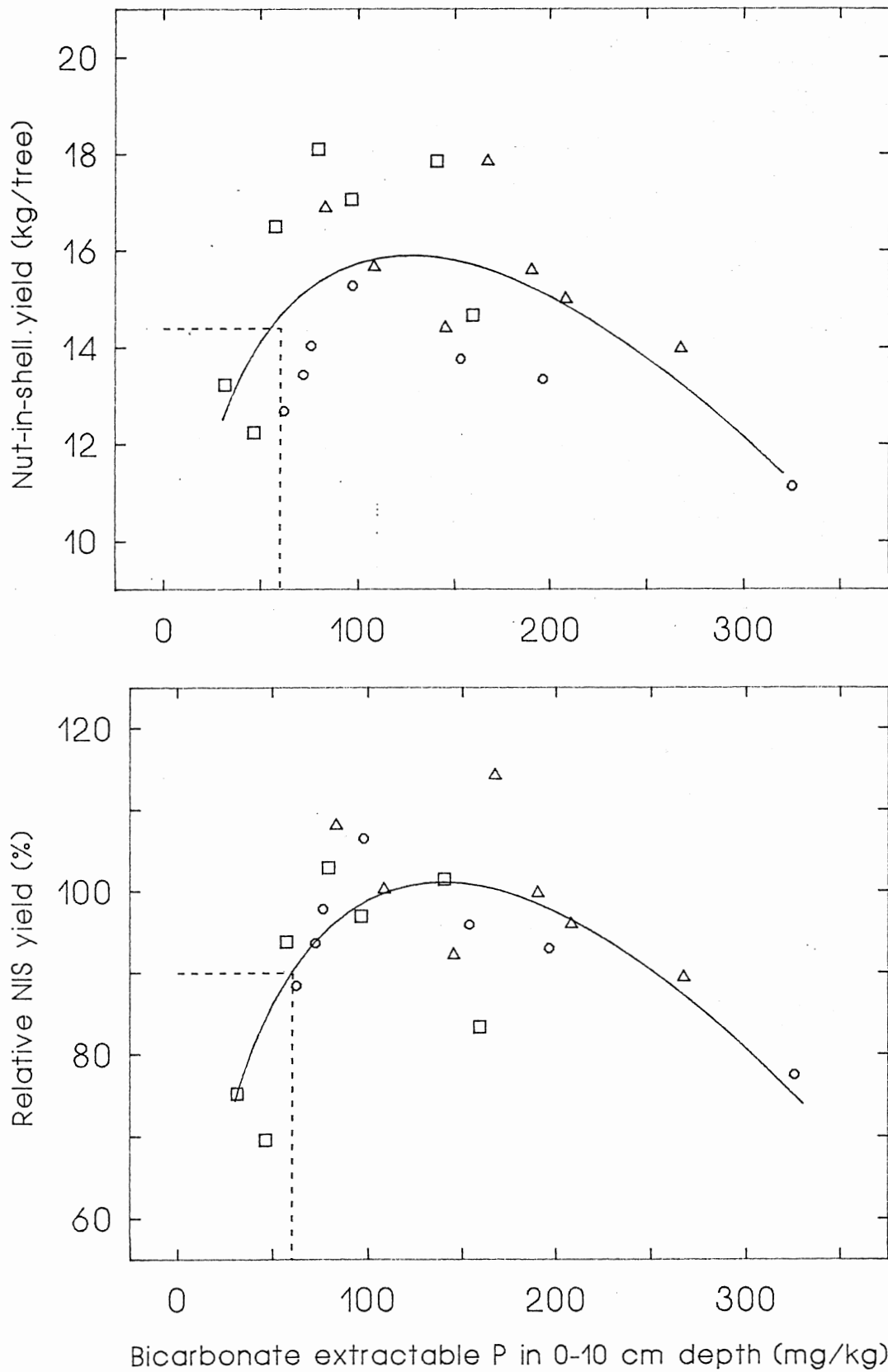


Figure 9. Yield and relative yield (1990 data) plotted against extractable soil phosphorus (Colwell method) for all sites. Curves were statistically fitted to the data. Dotted lines show soil test level at optimum yield.

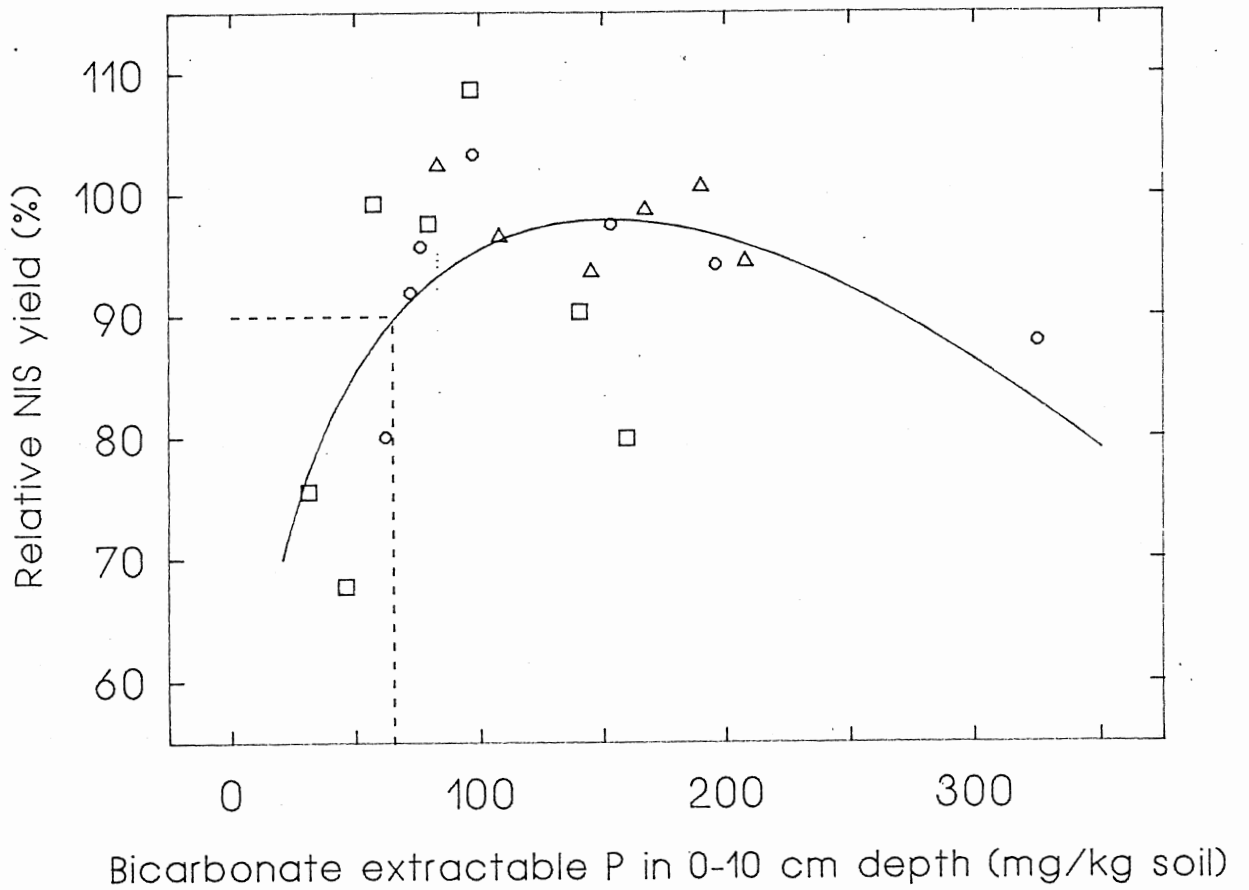


Figure 10. Relative nut-in-shell yield (from 3 year total yield) plotted against extractable phosphorus (Colwell method) for all sites. The curve was statistically fitted to the data. The dotted line shows the soil test level at optimum yield.

The concentrations of nutrients, other than phosphorus, in leaf samples were compared with the concentration ranges normally considered adequate (Robinson 1986) in macadamia. The concentrations of nutrient elements were in the adequate range at all sites except for copper (all sites) which would be considered marginal according to Robinson (1986).

These results suggest that the macadamia industry needs to look closely at the use of leaf phosphorus level (or more particularly the leaf tissue sampled) as an indicator of the tree's phosphorus status. The results obtained here may explain why many plantations repeatedly apply phosphorus fertilizer in an attempt to raise leaf phosphorus levels. This practice often results in high soil phosphorus levels but little change in leaf phosphorus levels.

#### *3.2.4 Relationships between yield and soil P test levels*

The soil test levels in the untreated soils, with the exception of soil solution phosphorus, successfully ranked the sites in order of response to P fertilizer application (Tables 1 and 5). The unamended soil at El Briale had the lowest soil P test levels and this was the only site at which NIS yields were significantly increased. Bicarbonate extractable phosphorus levels (untreated soil, Table 5) at El Briale, Haylock and Como Park were 28, 62 and 103 (mg/kg), respectively, and this ranking was reflected in the yield response data with a significant response, trend for increased yield and no yield increase being recorded at El Briale, Haylock and Como Park sites, respectively.

The relatively low bicarbonate extractable soil test level originally recorded at Como Park (38 mg P/kg, Table 1) would suggest that yields at this site would have been increased by P application. However, the inadvertent application of P-containing manures after the start of the trial increased the soil P level in the control plots to greater than 70 mg P/kg (0-10 cm depth).

Maximum yields at each site were similar (around 15-17 kg/tree each year) and therefore both absolute yields and relative yields were used to calibrate the soil test values. Relative yields were obtained as described in Appendix 1.

Figure 9 shows the relationships between soil test level (0-10cm depth) and each of nut-in-shell yield and relative yield across all sites (for 1990 yield). In each case there is a reasonable relationship indicating that bicarbonate (Colwell) extractable phosphorus levels in the soil may be used to indicate whether or not phosphorus fertilizer is required. Optimum yield (taken as 90% of maximum yield) was attained at an extractable (Colwell bicarbonate method) phosphorus level of 60 mg P/kg (Figure 9). Above this soil test value little or no yield increase would be expected from the application of phosphorus fertilizer. The total yields over the 3 year trial period were used to plot the relationship shown in Figure 10. Again, optimum yield (90% relative yield) was obtained for soil test values of around 60-70 mg P/kg soil. This 'critical' soil test level of 60-70 mg P/kg agrees reasonably well with the soil test level (Colwell bicarbonate method) of 50 mg P/kg obtained for macadamia seedlings in the glasshouse study (see section 3.1.3).

These results have important ramifications for the industry in that many managers are fertilising with phosphorus to much higher soil test levels. A limited survey of macadamia plantations in Queensland has shown that some have Colwell bicarbonate extractable phosphorus levels of more than 200 mg P/kg soil. In some instances soil test levels (Colwell bicarbonate extractable) are greater than 300 mg P/kg soil. Such levels are a result of repeated applications of phosphorus fertilizer.

Although this study was limited to only three field trial sites, it provides clear evidence that macadamia producers could save costs by not applying phosphorus when soil test levels (Colwell bicarbonate method) are greater than about 70 mg P/kg soil.

Just as importantly, the results show that when soil test levels exceed 150-200 mg P/kg a yield reduction is likely (Figures 9 and 10). It is not uncommon to observe chlorosis (pale yellow-green colour) on young macadamia leaves in plantations receiving large amounts of phosphorus fertilizer. Chlorosis can be a symptom of iron deficiency, and induced iron deficiency as a result of high rates of applied phosphorus may reduce yields. The mechanisms by which high levels of 'available' soil phosphorus can reduce the availability of iron (and other nutrients) to plants are well understood by soil scientists and plant nutritionists. It is recommended that macadamia producers consider their phosphorus fertilizer program in relation to the results of this study.

#### 4. CONCLUSIONS

Given the difficulty we had in finding established macadamia plantations with low levels of extractable phosphorus, it would appear that many plantations may already be adequately supplied with phosphorus. The results of this study have demonstrated that high levels of extractable soil phosphorus can reduce yields and also suggest that many producers can reduce operating costs by not applying phosphorus fertilizer when soil test levels (Colwell bicarbonate extractable) are above about 70 mg P/kg. In addition, the results suggest that the use of leaf phosphorus concentration as the sole diagnostic index is fraught with uncertainty.

In an established plantation the cost of fertilizer is usually less than 15% of the total cash outlay (Thew and Vock, 1989). A small but significant saving in operating costs would be made by not applying phosphorus fertilizer when soil test phosphorus values are high. On the other hand, results at the responsive site (El Briale) show that, where soil phosphorus levels are deficient, a relatively small cash outlay for phosphorus fertilizer would result in a substantial increase in cash receipts (50% increase in NIS yield at the El Briale site).

Finally, it is emphasised that the soil test calibrated in Figures 9 and 10 is the bicarbonate (Colwell 1963) method. This calibration permits interpretation of results obtained using this test method but not results from a different soil test procedure. Because the results presented were obtained from only three field sites, the soil test calibration should only be regarded as provisional.



## 5. ACKNOWLEDGMENTS

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## 7. APPENDIX 1

### *Calculation of relative yields used for soil test calibration.*

Relative yields are commonly used when a number of sites are used to obtain yield response data for soil test calibration. The objective of calibration is to develop a yield response measure that can be related to soil test level for a particular nutrient. Relative yields are used since it is recognised that local climatic and environmental conditions at each site may influence yield in addition to the nutrient of interest. In the present study this effect appears to have been minimal since maximum yields were of the same order at all sites.

#### *El Briale and Haylock sites:-*

A square-root quadratic relationship was fitted to the relationship between yield and rate of applied phosphorus (e.g. see Figure 7). The maximum yield was taken as that obtained from the square-root quadratic equation. The actual average yield for each treatment was expressed as a percentage of this maximum yield to give relative yield :-

Relative yield = Average treatment yield x 100/maximum yield.

#### *Como Park site:-*

At this site there was no significant treatment effect and no discernible trend in the yield data (Table 6). Yields for all treatments were averaged and the yield of individual treatments expressed as a percentage (relative yield) of the overall average yield.