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Macadamia yield and quality responses to phosphorus

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Abstract. Phosphorus fertiliser was applied to mature macadamia trees on 3 plantations with relatively low soil P in south-eastern Queensland at rates of 0, 10, 20, 40, 80, 160, and 320 kg P/ha at El Briale and Como Park and 0, 15, 30, 60, 120, 240, and 480 kg P/ha at Haylock. High rates of P were being applied to macadamias throughout the Australian industry and this study was designed to provide a basis for determining optimum application rates and critical soil P levels. Soil P was 33–199.5, 38.1–267.0, and 62.3–253.0 mg/kg at El Briale, Como Park, and Haylock, respectively. A tentative critical soil P concentration of 84–88 mg/kg was indicated, based on relative yields at El Briale and Haylock. Yield responsiveness to applied P was greatest at Haylock on a heavy soil that may have adsorbed P more readily, and had a higher P buffer capacity, than the lighter soils at the other sites. Leaf P was unresponsive to applied P, and hence soil P in this study. This is of concern since leaf P is used extensively to guide nutrition management. Further work is required to clarify relationships between leaf and soil P concentrations.

Additional keywords: kernel recovery, first grade kernel.

Introduction

Macadamia yield responses to phosphorus (P) have been documented on lava land or high phosphate fixing soils in Hawaii (Cooil *et al.* 1966; Shigeura *et al.* 1974), as well as on many of the red loam (krasnozem) soils in Australia (Newett 1987; Stock 1987). In fact, many of the soils on which macadamias are currently grown in Australia are low in phosphorus (Aitken *et al.* 1992). Attempts to overcome the limitation of phosphorus fixation in a krasnozem soil by frequent deep placement (up to 15 cm) of P fertiliser did not improve leaf P concentration, tree growth, or yield (I. Vimpany, pers. comm.). However, application of 2 kg pelletised fowl manure per tree resulted in increased leaf P concentration by *c.* 0.03% to the accepted critical concentration of 0.08%.

Aitken *et al.* (1992) confirmed that the critical leaf P concentration was 0.08%, based on 90% of whole plant top growth of macadamia seedlings. Associated critical soil P levels were 50 mg/kg for Colwell-extractable P. When the leaf Fe/P ratio was <0.07, growth was depressed and severe symptoms of iron chlorosis were apparent. Furthermore, when soil P was >100 mg/kg of Colwell-extractable P, proteoid root growth decreased. Despite this, Stock (1987) claimed that the optimum soil level for macadamia was >100 mg/kg. These conflicting reports reflect the need for further investigation on P fertiliser requirements of macadamias in commercial orchards.

Correct interpretation of any soil test requires calibration against yield. A large number of field sites, usually 15–50, are required to provide a sound basis for interpretation of the yield response to fertiliser applied (Rayment 1985; Moody and Bruce 1988). These yield responses are then related to soil test values to establish the optimum soil test value. This calibration is time-consuming and costly, and is not practical for macadamia, which often takes a long time to respond to fertiliser application. Soil tests were therefore calibrated for seedling macadamias grown in a range of soils in a glasshouse (Aitken *et al.* 1992) and field trials were established in macadamia plantations to verify the usefulness for practical fertiliser management.

Materials and methods

Three field trials were established in commercial orchards with relatively low soil P levels in south-eastern Queensland (Table 1). Como Park was compromised after fowl manure was inadvertently applied to trial trees. At each site, P was determined in the soil under each experimental tree. Because of variable soil P levels (Table 2), plots were stratified according to soil P and treatments were allocated accordingly (low P soils as controls, and increasing levels of applied P as soil P increased). This was done to achieve the desired ranges of soil P. Treatments consisted of 6 rates of P replicated 4 times and the controls replicated 8 times. The P was applied to the soil surface as triple

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Table 1. Soil properties at 3 field trial sites in established macadamia plantations in south-eastern Queensland

Site name	Clay (%)	Organic carbon (%)	ECEC[A] (mmol(+)/100 g)	pH[B]	Soil solution P[C] (µg P/L)	Bicarb. extr. P[D] (mg/kg)	Bray 1 extr. P (mg/kg)
El Briale	8	0.7	2	5.6	46	33	17
Como Park	11	0.8	2	5.8	68	38	24
Haylock	52	2.2	9	5.9	44	62	25

[A]Effective cation exchange capacity.
[B]1 6:5 soil : water.
[C]Phosphorus concentration in soil solution extracted from soil wet to field capacity (Warrell and Moody 1984).
[D]Colwell (1963) method.

Table 2. Mean soil P levels in surface soil (0–10 cm) at experimental sites in 1989 prior to fertilisation, 1990 immediately after fertilisation, and 1991, and coefficient of variation (CV%)
Como Park soil samples from 0–5 mm only analysed in 1991

Phosphorus applied (kg P/ha)	Soil P, bicarbonate-extractable (mg/kg)							
	El Briale			Como Park		Haylock		
	1989	1990	1991	1989	1990	1989	1990	1991
0	33	50.9	49.6	38.1	82.7	62.3	91.5	79.5
10	47	58.3	81.9	50.5	108.4			
15						71.8	77.8	86.1
20	54.8	77.9	101.0	56.5	145.0			
30						75.8	106.1	114.5
40	59.5	79.4	93.8	69.0	109.0			
60						78.3	89.8	108.4
80	63.8	95.6	117.1	79.0	190.0			
120						85.0	125.4	146.8
160	70.5	140.3	147.1	95.0	184.8			
240						95	156.1	148.4
320	88.5	159.0	199.5	113.5	267.0			
480						112.8	253.0	231.6
CV%	7.4	28.7	25.7	9.4	33.5	5.1	31.8	18.8

superphosphate (19.4% P). The rates applied were: 0, 10, 20, 40, 80, 160, and 320 kg P/ha at El Briale and Como Park, and 0, 15, 30, 60, 120, 240, and 480 kg P/ha at Haylock. Gypsum (calcium sulfate) was applied to each plot to balance the calcium and sulfur in the superphosphate so that P was the only varying factor across treatments. The P fertiliser was applied to 5 m by 5 m single-tree plots, centred on the tree. To achieve uniform distribution of the added fertiliser, each plot was subdivided into 1 m by 1 m subplots and appropriate amounts of the fertiliser uniformly applied to the subplot through a sieve. The fertiliser was applied in November 1989.

Experiments were carried out on varieties HAES 246 at the Haylock and Como Park sites and HAES 660 at El Briale. The management of trees was based on sound commercial practices for the respective plantations, except that phosphorus-containing fertilisers were excluded. All orchards were unirrigated.

Soil samples were collected in November 1989, 1990, and 1991, 5 cores of 8 cm diameter being taken from 0–5 cm and 5–10 cm depths in each plot and the respective depth intervals bulked. Soil samples were air-dried, sieved to <2 mm, and analysed for extractable P using the Colwell (1963) procedure (0.5 M $NaHCO_3$ at 1 : 100 soil : solution for 16 h extraction). At Como Park in 1991, only cores of 0–5 cm depth were analysed. The P soil concentration for the 0–10 cm strata was calculated as the average of the samples from 0–5 cm and 5–10 cm depths.

Tree growth was assessed by trunk girth measurements annually for 4 years. Nuts were harvested 2–3 times between April and August each year, and yield (nut-in-shell at 10% moisture) and quality (kernel recovery, KR, and % first grade kernel, G1K) recorded [KR = (kernel weight/nut-in-shell weight) × 100]. First grade kernel has an oil content of 72% or greater and is determined by the percentage weight of oven-dried kernels that float in water. The mean yield in each year at all sites was plotted against mean soil P (0–10 cm strata) in the previous year, or if not measured in that year, the last soil P measurements were used. Mitscherlich curves (Payne 2000) with the number of trees as weights were fitted to determine maximum yield. In those years in which the standard Mitscherlich curve did not satisfactorily describe the data, e.g. the data points were on a plateau, maximum yields were determined by constraining the Mitscherlich curve such that the yield was zero when the mean soil P (0–10 cm strata) was small, i.e. less than 15 mg/kg. Relative yield was then calculated to enable comparisons in yield response across years and sites:

$$\text{Relative yield} = 100 * \text{mean treatment yield/maximum yield}$$

Mitscherlich curves were then fitted to the relative yields to determine the critical soil P concentration at which 90% maximum relative yield was obtained. A similar process was undertaken using the mean soil P (5– 10 cm strata) as this avoided any surface contamination.

Samples of mature leaves from the second whorl of current season's growth were collected from each tree in late October (Stephenson and Cull 1986) and analysed for P.

Results

Changes in soil P (0–10 cm) under control trees from 1990 to 1991 indicate variability in the data (Table 2). Nevertheless, applied P was reflected in soil P concentrations and the soil P levels of the plots in 1991 were correlated with those in 1990 (El Briale, $r = 0.91$; Haylock, $r = 0.83$). Leaf P concentrations did not reflect P applied, except partially at Haylock in 1990, the year after P was applied (Table 3).

An abnormally high yield was obtained at El Briale in 1991 at 95.6 mg/kg of soil P (0–10 cm in 1990). Yields at Haylock in 1993 and 1994 were higher when soil P in 1991 was 108.4 mg/kg (0–10 cm) or above when compared with yields from soil with P at 79.5 mg/kg (Table 4). Maximum yield could be predicted with confidence at Haylock in 1992, 1993, and 1994 (Table 5). A common Mitscherlich curve could be fitted to the relative yield at the Haylock site in 1992, 1993, and 1994 (Fig. 1):

$$Y = 100.04 - 1522888e^{-0.1349P}$$

where Y is relative NIS yield (%), and P is bicarbonate-extractable P (mg/kg) at 0–10 cm.

Optimum yield (90% of maximum relative yield) was obtained at a critical bicarbonate-extractable soil P concentration of *c.* 88 mg/kg at 0–10 cm. At soil P concentrations above this, average relative yield did not increase.

A common Mitscherlich curve not constrained fitted to the relative yield response at El Briale in 1992 and 1993 shows a tentative critical soil P concentration of 84 mg/kg at 0–10 soil P (Fig. 2):

Table 3. Mean leaf P concentrations in experimental trees in 1990 immediately after fertilisation, and in 1991

s.e.d.1 is the standard error of difference between the 8 trees receiving no application and any of the other groups (4 trees); s.e.d.2 is the standard error of difference between the groups with 4 trees. Leaf P concentrations only done on bulked samples in 1991. Means followed by the same letter are not significantly different at $P = 0.05$

P added (kg P/ha)	Mean soil P (mg/kg)		Leaf P concentration (%)	
	1990	1991	1990	1991
		El Briale		
0	50.9	49.6	0.11	0.07
10	58.3	81.9	0.09	0.06
20	77.9	101.0	0.08	0.06
40	79.4	93.8	0.09	0.07
80	95.6	117.1	0.11	0.07
160	140.3	147.1	0.11	0.07
320	159.0	199.5	0.14	0.08
s.e.d.1			0.021	
s.e.d.2			0.024	
		Como Park		
0	82.7	–	0.07	0.07
10	108.4	–	0.07	0.07
20	145.0	–	0.07	0.05
40	109.0	–	0.06	0.06
80	190.0	–	0.07	0.05
160	184.8	–	0.08	0.06
320	267.0	–	0.10	0.07
s.e.d.1			0.013	
s.e.d.2			0.015	
		Haylock		
0	91.5	79.5	0.059a	0.05
15	77.8	86.1	0.065a	0.05
30	106.1	114.5	0.070a	0.06
60	89.8	108.4	0.070a	0.06
120	125.4	146.8	0.075ab	0.06
240	156.1	148.4	0.093b	0.06
480	253.0	231.6	0.073a	0.06
s.e.d.1			0.0082	
s.e.d.2			0.0094	

Table 4. Nut-in-shell (NIS) yield of macadamia trees at different regimes of soil P (0–10 mg/kg) in 1990 and 1991

s.e.d.1 is the standard error of difference between the 8 trees receiving no application and any of the other groups (4 trees); s.e.d.2 is the standard error of difference between the groups with 4 trees. Within parameters, means followed by the same letter are not significantly different at $P = 0.05$

P added (kg P/ha)	Mean soil P (mg/kg)		Yield (kg NIS/tree)			
	1990	1991	1991	1992	1993	1994
			El Briale			
0	50.9	49.6	6.3a	12.9	16.7	14.6
10	58.3	81.9	4.6a	11.7	16.4	8.4
20	77.9	101.0	8.4ab	16.9	17.5	14.3
40	79.4	93.8	6.2a	16.1	24.5	14.8
80	95.6	117.1	10.8b	18.0	22.3	19.0
160	140.3	147.1	4.6a	15.6	22.7	19.8
320	159.0	199.5	4.4a	14.6	24.2	20.6
s.e.d.1			1.81	2.59	4.61	3.75
s.e.d.2			2.09	2.99	5.33	4.33
			Como Park			
0	82.7	–	14.9	19.5	16.7	18.9
10	108.4	–	14.9	17.8	15.5	16.1
20	145.0	–	14.2	18.3	17.2	19.1
40	109.0	–	13.6	18.0	17.7	20.8
80	190.0	–	15.2	19.6	15.8	18.9
160	184.8	–	14.1	18.2	16.3	18.5
320	267.0	–	17.4	25.5	18.6	22.2
s.e.d.1			1.74	3.10	2.14	2.85
s.e.d.2			2.00	3.58	2.47	3.29
			Haylock			
0	91.5	79.5	13.1	10.3	11.0a	9.4a
15	77.8	86.1	15.4	12.6	14.4ab	13.2ab
30	106.1	114.5	14.6	14.5	13.8ab	12.6ab
60	89.8	108.4	16.0	15.3	17.0b	15.6b
120	125.4	146.8	15.5	14.7	16.7b	16.5b
240	156.1	148.4	14.2	14.9	16.1b	14.8b
480	253.0	231.6	13.9	14.6	17.2b	16.6b
s.e.d.1			2.11	2.57	2.12	2.45
s.e.d.2			2.44	2.97	2.44	2.12

Table 5. Maximum yields determined by Mitscherlich curves on bicarbonate-extractable P (mg/kg) at 0–10 cm

Year	Maximum yield (kg/tree)	% Variation explained
	El Briale	
1991	6.8[A]	0
1992	15.9[A]	26.4
1993	22.7[A]	39.7
1994	18.0[A]	0.3
	Como Park	
1991	15.0[A]	0
1992	20.2[A]	0
1993	16.9[A]	0
1994	19.5[A]	0
	Haylock	
1991	14.5[A]	0
1992	14.8	97.6
1993	16.2	74.7
1994	15.3	72.9

[A]Constrained.

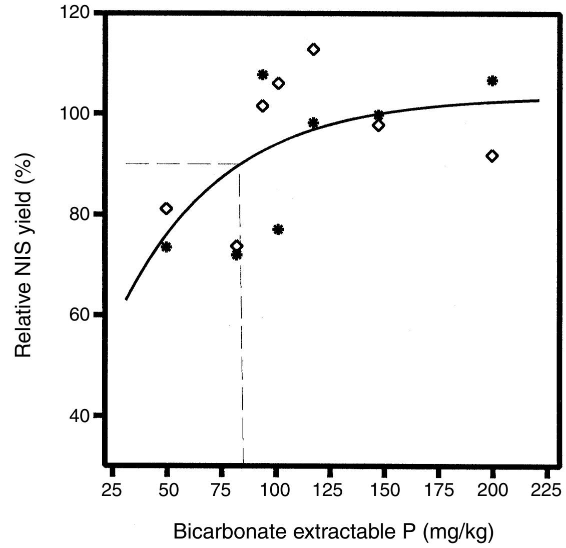

Fig. 2. Relative nut-in-shell yield of macadamia in response to soil bicarbonate-extractable P (0–10 cm in 1990) at the El Briale site in 1992 (◇) and 1993 (∗), with fitted Mitscherlich curve.

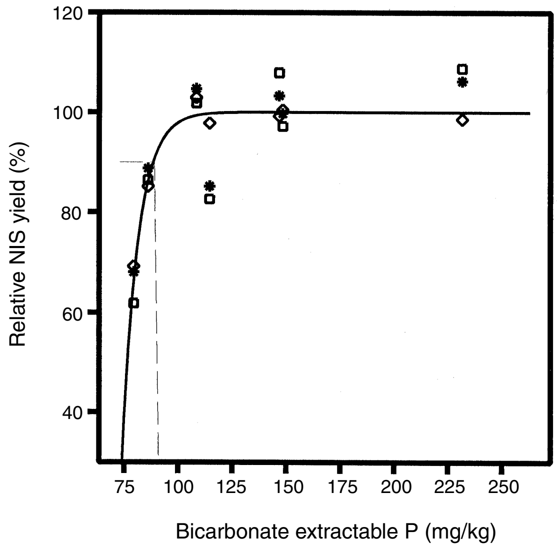

Fig. 1. Relative nut-in-shell yield of macadamia in response to soil bicarbonate-extractable P (0–10 cm in 1990) at the Haylock site in 1992 (◇), 1993 (∗), and 1994 (□), with fitted Mitscherlich curve.

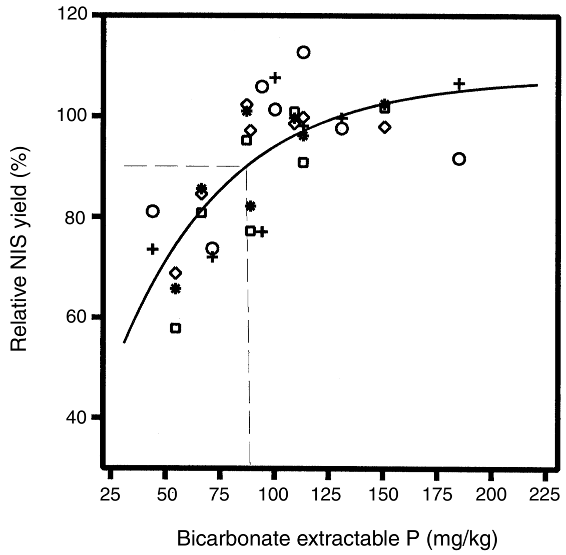

Fig. 3. Relative nut-in-shell yield of macadamia in response to soil bicarbonate-extractable P (5–10 cm in 1990) at the Haylock site in 1992 (◇), 1993 (∗), and 1994 (□), and El Briale site in 1992 (○) and 1993 (+), with fitted Mitscherlich curve.

$$Y = 103.5 - 77.63e^{-0.02092P}$$

Although a common Mitscherlich curve could not be fitted to relative yield data from the 3 sites based on 0–10 cm soil P, a common curve could be fitted to 5–10 cm soil P for Haylock in 1992, 1993, and 1994 and El Briale in 1992 and 1993 ($Y = 107.7 - 97.07\ e^{-0.01957P}$), which gave a critical soil P concentration of 87 mg/kg (Fig. 3).

Mitscherlich curves could not be fitted to relative yields for Como Park 1991, 1992, 1993, and 1994. However, values of the soil P (0–10 cm) concentrations were already approaching the soil concentration at which relative yields plateaued at El Briale, a site with similar soil. Fig. 4 shows the relative yields at Como Park compared with the El Briale Mitscherlich curve from Fig. 2. Mitscherlich curves could not be fitted to relative yields for Haylock 1991 (Fig. 5) and El Briale 1991 and 1994 (Fig. 6). These data are shown with the Haylock and El Briale curves of Fig. 1 and Fig. 2, respectively.

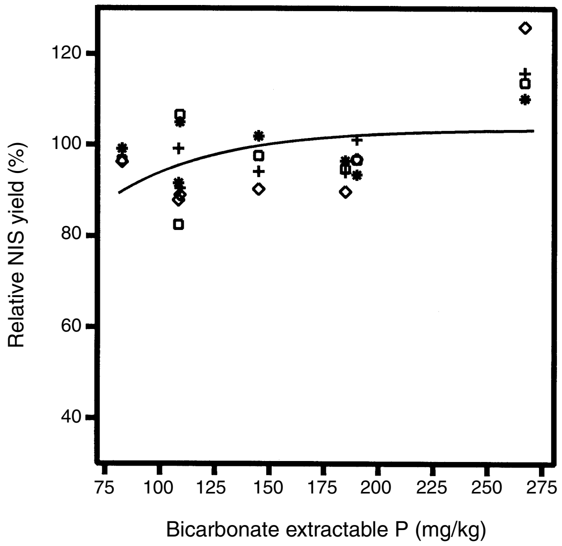

Fig. 4. Relative nut-in-shell yield of macadamia in response to soil bicarbonate-extractable P (0–10 cm in 1990) at Como Park in 1991 (+), 1992 (◇), 1993 (∗), and 1994 (□), with Mitscherlich curve fitted to El Briale 1992 and 1993 superimposed from Fig. 2 for comparison.

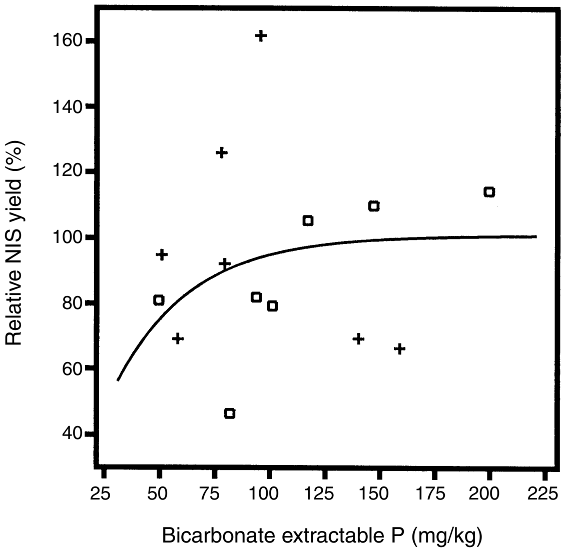

Fig. 6. Relative nut-in-shell yield of macadamia in response to soil bicarbonate-extractable P (0–10 cm in 1990) at El Briale in 1991 (+) and 1994 (□), for which a Mitscherlich curve could not be fitted, with Mitscherlich curve fitted to El Briale 1992 and 1993 superimposed from Fig. 2 for comparison.

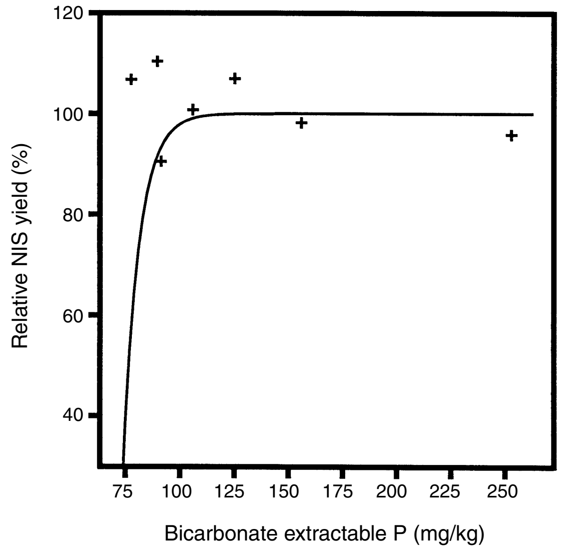

Fig. 5. Relative nut-in-shell yield of macadamia in response to soil bicarbonate-extractable P (0–10 cm in 1990) at Haylock in 1991 (+), for which a Mitscherlich curve could not be fitted, with Mitscherlich curve fitted to Haylock 1992, 1993, and 1994 superimposed from Fig. 1 for comparison.

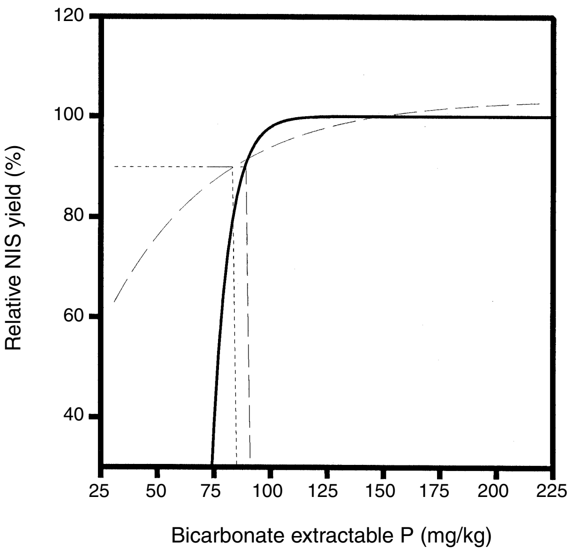

Fig. 7. Comparison of Mitscherlich curves and critical soil P concentrations for Haylock (—) and El Briale sites (– –). The horizontal line indicates optimum yield (90% of maximum relative yield) and vertical lines indicate corresponding optimum soil P for the two sites.

Fig. 7 shows the different response in yield to soil P for different soil types at Haylock and El Briale.

Kernel recovery (KR) and first grade kernel (G1K) were sometimes lower at low levels of P (Table 6). Differences were significant at the Haylock site in 1992 for both KR and G1K and for G1K in 1993. When soil P at El Briale was 81.9 mg/kg, G1K was lower than at other levels of soil P. Tree growth was not affected by P applications (data not presented).

Discussion

The widespread use of phosphorus fertiliser made it difficult to find macadamia orchards with low soil P status, suggesting that many plantations may already be adequately

Table 6. Kernel recovery and first grade kernel of macadamia trees at different regimes of soil phosphorus in 1990 and 1991 (0–10 cm) at 3 sites

s.e.d.1 is the standard error of difference between the 8 trees receiving no application and any of the other groups (4 trees); s.e.d.2 is the standard error of difference between the groups with 4 trees. Within parameters, means followed by the same letter are not significantly different at $P = 0.05$

P added	Mean soil P		Kernel recovery (%)				First grade kernel (%)			
(kg P/ha)	1990	1991	1991	1992	1993	1994	1991	1992	1993	1994
				El Briale						
0	50.9	49.6	33.3	36.7	37.6	36.2	97.1	98.7b	97.2	97.1
10	58.3	81.9	32.5	36.8	35.7	37.5	94.4	94.9a	89. 4	93.2
20	77.9	101.0	35.0	37.7	37.6	36.1	95.9	97.4ab	94.77	93.9
40	79.4	93.8	33.5	36.8	37.6	37.4	98.4	97.8b	95.1	94.9
80	95.6	117.1	32.6	36.3	36.1	35.3	95.8	97.6b	94.6	93.6
160	140.3	147.1	32.4	37.9	38.2	36.3	96.1	98.5b	97.5	97.2
320	159.0	199.5	32.5	37.8	38.5	35.8	95.7	99.7b	98.8	97.8
s.e.d.1			1.22	0.96	0.82	0.87	1.94	1.06	2.61	2.00
s.e.d.2			1.41	1.10	0.95	1.00	2.24	1.22	3.02	2.31
				Como Park						
0	82.7	–	34.6	34.8	37.1	37.5	97.7	94.0	96.6	92.7
10	108.4	–	34.7	34.3	35.9	37.2	98.8	94.1	95.0	90.4
20	145.0	–	35.2	34.1	37.3	37.6	97.0	90.0	96.5	91.1
40	109.0	–	34.3	33.8	36.0	37.0	96.7	87.4	94.3	89.5
80	190.0	–	37.2	36.5	38.5	39.2	98.3	95.1	98.4	94.2
160	184.8	–	36.0	34.7	37.1	38.6	98.8	93.8	97.2	91.9
320	267.0	–	35.0	35.5	37.8	38.4	97.4	95.1	94.8	92.0
s.e.d. 1			1.14	0.97	0.85	1.12	1.19	2.89	2.17	2.05
s.e.d. 2			1.32	1.12	0.98	1.30	1.37	3.34	2.51	2.36
				Haylock						
0	91.5	79.5	33.1	31.3a	34.0	35.9	95.6	79.5a	91.2a	85.5
15	77.8	86.1	33.7	32.8ab	34.9	35.8	98.9	95.7b	94.1ab	83.2
30	106.1	114.5	33.9	34.1b	35.0	36.0	99.1	94.2b	97.3b	89.3
60	89.8	108.4	33.8	34.2b	35.4	35.5	98.7	95.1b	97.8b	89.3
120	125.4	146.8	33.9	33.3ab	34.9	34.7	99.3	96.0b	97.7b	92.5
240	156.1	148.4	34.1	34.3b	36.0	35.5	98.1	97.5b	98.4b	85.6
480	253.0	231.6	33.9	34.2b	36.6	36.3	99.6	97.2b	98.4b	88.8
s.e.d.1			0.62	1.00	0.90	0.64	1.50	5.38	2.48	4.14
s.e.d.2			0.71	1.16	1.04	0.74	1.74	6.21	2.86	4.78

supplied with P. Bruce and Rayment (1982) considered that bicarbonate-extractable P 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. Moreover, Cumming and Elliot (1991) suggested that bicarbonate-extractable P values of 200–300 would result in P toxicity in most crops, but this was not evident in this study. Critical Colwell soil P concentration for macadamia seedling growth across a wide suite of soils was 50 mg/kg (Aitken *et al.* 1992). Hence, the lowest soil P concentrations in this present study may not have been low enough to elicit clear-cut responses.

The unresponsiveness of leaf P concentrations to applied P, and hence soil P concentrations, is of concern because leaf analysis is used extensively in the macadamia industry to guide nutrition management. Nevertheless, leaf P was in the adequate range at El Briale in 1990 but on the low side at the Haylock site. Caution is needed in interpreting leaf P concentrations. Further work to clarify the relationships between leaf and soil P and yield responses would be desirable.

Yields were low at El Briale in 1991, the only year when yield responded to P applications at this site. Rainfall in the preceding season was very low (well below average during the preceding 9 months), resulting in poor flowering. The apparently greater responsiveness of yield to applied P at Haylock was probably related to the heavy clay soil type, which would adsorb P, making it less available compared with the light sandy soil at El Briale, which is likely to have lower P-fixing ability (Moody and Bolland 1999). Despite control soil P (0–10 cm) of 79.5 mg/kg in 1991, leaf P concentrations at Haylock were 0.05%, whereas at El Briale the low soil P (0–10) of 49.6 mg/kg in control plots was not reflected in leaf P concentrations, which were all in the adequate range (0.07%). The long-term residual effects of applied P (Barrow 1980) were reflected in soil P but not in leaf P. Soil and leaf P were not correlated in this study and leaf P was therefore a poor indicator of soil P and of yield responsiveness to P status.

Although yield responses to P were not consistent, relative yields at El Briale and Haylock indicated a tentative critical soil P concentration of 84–88 mg/kg at 0–10 cm. Higher relative yields were not obtained at higher soil P levels. This critical value is slightly higher than that reported by Aitken *et al.* (1992) based on macadamia seedling growth. Similarly, applications of P fertiliser greater than 60–80 kg P/ha on similar soils are unlikely to increase yields. In fact, high rates of P depressed yields below the optimum at El Briale in 1991. This is consistent with the data of Cooil *et al.* (1966), who showed depressed macadamia yields when about 2 kg P was applied to macadamia trees (leaf P >0.14%). Moreover, Shigeura *et al.* (1971) reported that leaf P >0.18% induced Fe deficiency. Although leaf P was unresponsive to applied P in the present study, caution should be exercised with heavy applications of P to macadamias. These have been necessary, however, in the P-fixing krasnozem soils of northern New South Wales macadamia plantations.

Phosphorus buffer capacity of a soil is a measure of the amount of P that must be added to the soil to raise the solution P concentration by one unit. Soils with a high buffer capacity (or high P 'fixing' ability) require a large amount of added P to increase their solution P concentration. P arrives at the root surface by diffusion, so solution P concentration is one of the factors that affects P availability. Colwell extractable P is a measure of sorbed plus solution P, and it has been documented for several crops/pastures that, as P buffer capacity increases, so does the 'critical' Colwell extractable P value required for maximum yield (Moody and Bolland 1999). In some cases, critical Colwell-extractable P was shown to increase with increasing clay content (e.g. annual temperate pasture) because, in general, P buffer capacity is positively correlated with clay content. The soil at Haylock had a higher clay content than that at El Briale (8 cf. 52%). It can therefore be inferred that the Haylock site has a higher P buffer capacity. Although the critical soil P for the Haylock site was only marginally higher than at El Briale, yield was unresponsive below 79.5 mg/kg of soil P, above which the rate of exponential increase of the Haylock curve is much higher. At El Briale, macadamia yield is more responsive to incremental increases in soil P up to the critical soil P concentration.

Traditionally, it is difficult to demonstrate yield responses to P in perennial crops. For example, there was an 8-year delay before a yield response was obtained to P applications to grapes (Tulloch and Harris 1970). The lack of consistent tree growth and yield responses in this study is not surprising. Nevertheless, the results provide guidance for P fertiliser management for macadamias in Australia. Maintaining critical soil P concentrations of 90 mg/kg at 0–10 cm should optimise macadamia yields provided other factors are non-limiting. This is a valuable management tool, but because the results presented were obtained from only 3 field sites, the soil test calibration should only be regarded as provisional.

The results also suggest that the use of leaf P concentration as the sole diagnostic index is fraught with uncertainty and further work is needed to determine its reliability as an indicator of tree P status.

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