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Leaf nitrogen as a guide for fertilising macadamia

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Summary. Despite the lack of evidence for a critical level of leaf nitrogen in macadamia, fertiliser management has been largely based on tentative standards for high yielding trees. Trees on a lower plane of nitrogen nutrition, however, produced higher yields of good quality nuts. This study was therefore carried out to establish the relationship between yield and nitrogen status of trees. Three rates of nitrogen fertiliser (0.5, 1.5 and 2.5 kg urea/tree.year; 230, 690 and 1150 g nitrogen respectively) were applied to macadamia trees in 1 of 5 application strategies: 1 application in April (floral initiation); 2 applications, one in April and one in June (inflorescence development); 3 applications, April, June and November (rapid nut growth and premature nut drop); 4 applications, April, June, November and January (oil accumulation); and 12 monthly split applications. Multiple applications were all equal in size. The association between high yields and low nitrogen status was confirmed. In some, but not all, years, yield was negatively correlated with leaf nitrogen, accounting for 47 and 59% of the variation in yield of commercially acceptable nuts (>19 mm diameter) in 1991 and 1993, respectively. It is therefore recommended that the standard for leaf nitrogen in macadamia be lowered from 1.4–1.5 to 1.3% under Australian conditions. These results raise concerns at the current trend for leaf nitrogen to be as high as 1.8%. It would be prudent to cease nitrogen applications on at least a small experimental block until leaf nitrogen declined to 1.3% and then maintain this level for at least 3 years and monitor yields.

Introduction

Although nitrogen (N) fertiliser accounts for only a relatively small proportion of operating costs in macadamia orchards (Thew and Vock 1989), it has a strong influence on tree phenology, productivity and kernel quality (Stephenson and Gallagher 1989*a*, 1989*b*). Stephenson and Gallagher (1989*b*), for instance, reported that low rates of N applied in small, regular doses consistently produced higher yields and improved quality compared with single applications of higher rates of N. It is also important that fertiliser strategies are used to maximise the efficiency of applied N. Community environmental awareness dictates that excessive applications are avoided.

Fertiliser management in macadamia orchards has traditionally been based on leaf nutrient concentrations, the standards initially being developed in Hawaii (Hirae 1976), partly based on vegetative growth responses (Cooil *et al.* 1953). Stephenson and Cull (1986) recommended tentative leaf nutrient standards, based on monitoring 3 well-managed orchards in south-east Queensland. The best time for sampling was in October when levels of macronutrients were most stable. The range for N was a conservative 1.4–1.5%, although most of the Australian trees had leaf concentrations of 1.4% or less. In subsequent field research, high yields of macadamias were associated with much lower concentrations of N (1.2%, Stephenson and Gallagher 1989*a*). It is therefore important to provide a more critical assessment of the usefulness of leaf analysis in macadamia production and to base standard levels on tree yield responses.

This study was carried out to assess timing, number of applications and rates of N fertiliser on macadamia yield and quality. The reliability of leaf N concentrations as a fertiliser management tool was assessed and appropriate standards recommended.

Materials and methods

A total of 180, 15-year-old Keaau (HAES 660) macadamia trees grown at 200 trees/ha in a deep, well-drained, red clay loam soil in a commercial orchard near Mt Bauple, Queensland (lat. 26ºS, alt. 75 m), were selected for this 6 year study. These trees had also been used in a previous N fertiliser study (Stephenson and Gallagher 1989*a*, 1989*b*; Stephenson *et al.* 1989). Leaf analyses were carried out for N in October each year from 1987 to 1993 to ensure that nutrients other than N did not limit tree growth and production during the experiment. In the 1987 and 1988 seasons, leaf samples were taken for N analysis on several occasions from late October to late January. Since similar results were obtained in both years, only data
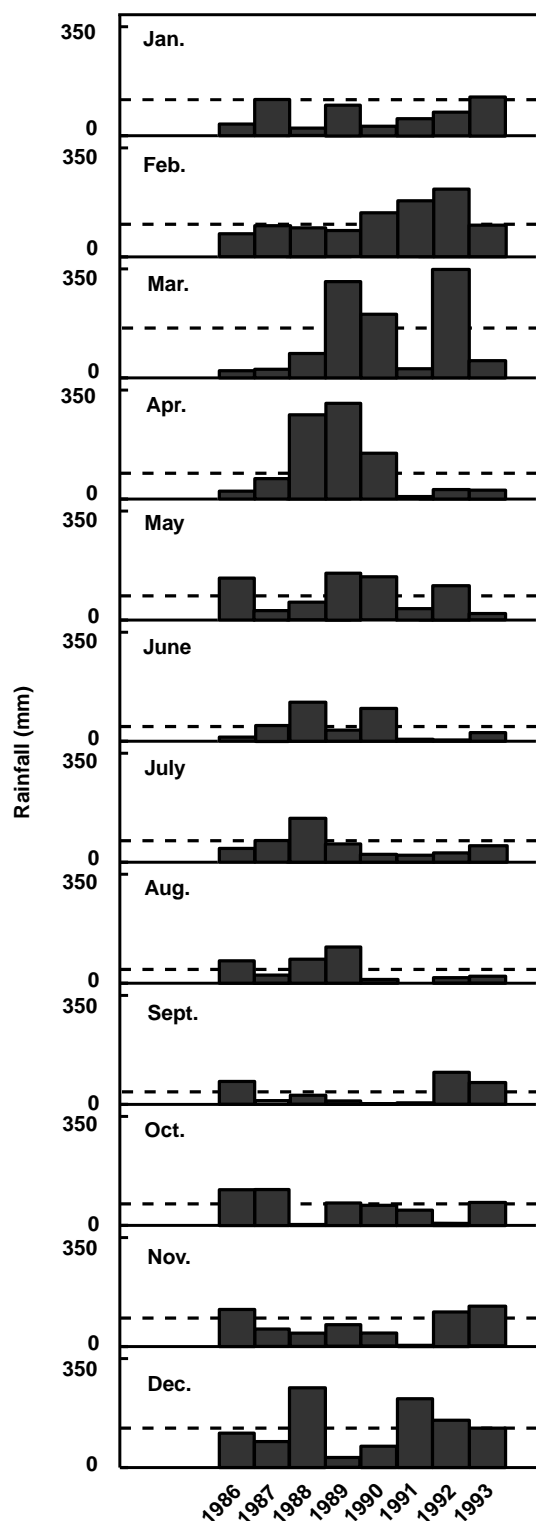
Figure 1. Monthly rainfall at the experimental site from 1986 to 1993. Dotted lines represent 20-year mean, monthly rainfall data.

from 1987 will be presented. Plots were irrigated after each fertiliser application, and as required at other times to ensure that water was not limiting. Standard orchard operations (O'Hare and Vock 1990), including pest, disease and weed control, were carried out as required.

Treatments

A split-plot, randomised block design was used, consisting of 5 application strategies and 3 rates of N in 4 replicated rows. Plots contained 9 trees each, with subplots of 3 trees. The main treatments (application strategies) were: (i) application of N in April (floral initiation); (ii) 2 equal applications of N, one in April and one in June (inflorescence development); (iii) 3 equal applications of N, one each in April, June and November (rapid nut growth and premature drop); (iv) 4 equal applications of N, one in April, June, November and January (oil accumulation); and (v) monthly, equal, split applications.

Subtreatments consisted of 0.5, 1.5 and 2.5 kg urea/tree.year (230, 690 and 1150 g N respectively). A nil fertiliser control was not included because of concern for tree health by the cooperating orchardist.

Data collection

Leaf and soil nutrient data were collected as described by Stephenson and Gallagher (1989*a*) and Stephenson *et al.* (1986).

Whole-plot yield was based on total nut-in-husk weight at field moisture. Subsamples of about 5 kg per plot were taken, dehusked, and weighed to determine the weight of nut-in-shell (NIS) at field moisture. They were then oven-dried at 60°C and yield of NIS adjusted to the industry standard of 10% moisture. Assessments of kernel recovery and the percentage of first grade kernels were carried out (R. A. Stephenson and E. C. Gallagher unpublished data).

Rainfall data (Fig. 1) were recorded from a standard weather station on the orchard. Temperature data were incomplete.

Statistical analyses

Data were subjected to standard split-plot analysis of variance. Where appropriate, split-split-plot analysis of variance was used with time as the sub-subplot factor. Correlations between nut yield and leaf N contents were calculated.

Results and discussion
Nitrogen status in orchard

Leaf nitrogen concentrations. Mean leaf N in October averaged 1.4% (data not shown) which is within the tentative range for the Australia industry set by Stephenson and Cull (1986). Leaf N reflected N fertiliser applied, increasing significantly ($P<0.05$) from 1.27% at low N to 1.39 and 1.46% at intermediate and high rates of N respectively (data not shown).

In late October and early December, mean leaf N was slightly but significantly ($P<0.05$) higher (1.53–1.55% N) than in late December to late January (1.49% N, data not shown). Leaf N declined in late December–January, corresponding to oil accumulation, except where N fertiliser was applied at this time (Table 1). Table 1 also shows the depletion of leaf N from October to December where N was restricted to the early phases of the phenological cycle (inflorescence initiation and early raceme development, April and June). In other application strategies, the N applied in both November and January, or monthly, was sufficient to maintain leaf N concentrations. This may have an important influence on photosynthesis (Lugg and Sinclair 1981; DeJong 1982; Syvertsen 1984) and hence productivity at critical stages of nut development. On the first sampling date, the current N applications for November had not been applied, hence the slightly lower leaf N concentrations. The same response was noted from October and November leaf sampling in 1988. These data indicate the importance of sampling leaves before the critical oil accumulation stage when leaf concentrations are relatively stable. Sampling during late spring or early summer may be misleading due to the draw-down on N reserves during this apparently high demand period.

Table 1 also shows that leaf N in December reflects N application in the previous month. This response was most rapid at the intermediate rate of N from 4 split applications, being detected in early December (Fig. 2). For the low rate of N in 4 applications, the increased leaf N was not detected until the late December sampling (Fig. 2). The November N in 3 split applications for all rates of N was reflected in higher leaf N in early December (Table 1). The difference between these 2 treatments was that in the latter, a third more N was applied in November. Similarly, applications of N in early January were reflected in higher leaf N later that month. This was particularly apparent with monthly applications at the low rate of N and with the 4 split

application treatments at intermediate and high rates of N (Fig. 2), but not at the low rate of N.

Leaf N concentrations in the first 3 years of the trial were generally higher (mean 1.40–1.53%) than in the last 4 years (≤1.33%, $P<0.01$). This may partly reflect residual effects from the previous N fertiliser experiment. Figure 3 shows relatively stable levels over the first 3 years of the trial when trees were apparently adjusting to imposed N regimes. Thereafter leaf N declined steadily from 1989 to 1991 and then levelled off from 1991 to 1993.

Soil nutritional status. Analysis of soils under experimental trees was carried out at the completion of this study to assess the extent to which N fertiliser applications over the previous 6 years had influenced soil chemistry. All parameters analysed except extractable boron were influenced by the rate of N ($P<0.05$) but not by the application strategy, or timing (Table 2). Soil pH at this site was inherently high, as reflected in the value for the low N treatment. Higher rates of N caused some acidification which would have been beneficial to macadamia growth from the work of Aitken *et al.* (1990) and Stephenson *et al.* (1996).

Table 1. Effect of method of nitrogen fertiliser application on concentration of N in index leaves of macadamia, cultivar Keaau, at four sampling dates in 1987–88

Values are the mean of four replicates pooled over three rates of N application

l.s.d. ($P = 0.05$) = 0.05 for comparing differences between dates within each time of application; l.s.d. ($P = 0.05$) = 0.08 for all other comparisons

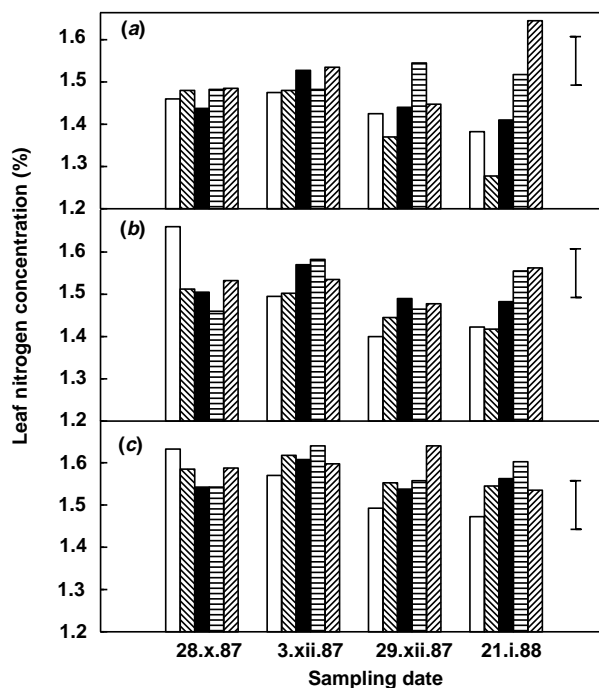| Time and number of applications	28.x.87	2.xii.87	20.xii.87	21.i.88
Apr.; 1	1.58	1.51	1.44	1.43
Apr., June; 2	1.53	1.53	1.46	1.41
Apr, June, Nov.; 3	1.50	1.57	1.49	1.49
Apr., June, Nov., Jan.; 4	1.50	1.57	1.52	1.56
Monthly; 12	1.54	1.56	1.52	1.58

Figure 2. Effect of rate of nitrogen, (*a*) 230, (*b*) 690 and (*c*) 1150 g N/tree.year, and fertiliser application strategy: 1 (open bar), 2 (reverse-inclined, striped bar), 3 (closed bar), 4 (horizontally striped bar), or 12 (inclined, striped bar) split applications on the N concentration in index leaves of macadamia, cultivar Keaau, at 4 sampling dates in 1987–88. Vertical bars indicate l.s.d. values at $P = 0.05$.

Increasing rates of N substantially increased soil nitrate and electrical conductivity levels, but, in general, they still tended to be low or within acceptable limits for fruit trees (Chapman 1961). On the other hand, phosphorus (P) concentrations tended to increase. This trend is possibly associated with the decline in organic carbon, resulting in mineralisation of P from the organic matter which had broken down. Nevertheless, P concentrations were all in the optimum range (Aitken *et al.* 1992). All cation levels declined, as did the cation exchange capacity. The decrease in cation exchange capacity was probably due to the decrease in pH. This effect is typical of variable charge soils in tropical and subtropical Australia. It is also likely that the more rapid breakdown of organic matter with increasing rates of N contributed to the reduction in cation exchange capacity. On this soil, all organic carbon levels were in the low range (Table 2). Magnesium concentrations tended to be low, potassium concentrations were in the optimum range but other cation concentrations were acceptable.

Yield

The 3 years after treatments had become established (1989, 1990 and 1991) were best for yield (Fig. 4). Rainfall in April and March 1988, 1989 and 1990 (Fig. 1) was much higher than in other years and may have led to more prolific flowering and hence yield in the following season. Multiple regression analysis of an extensive
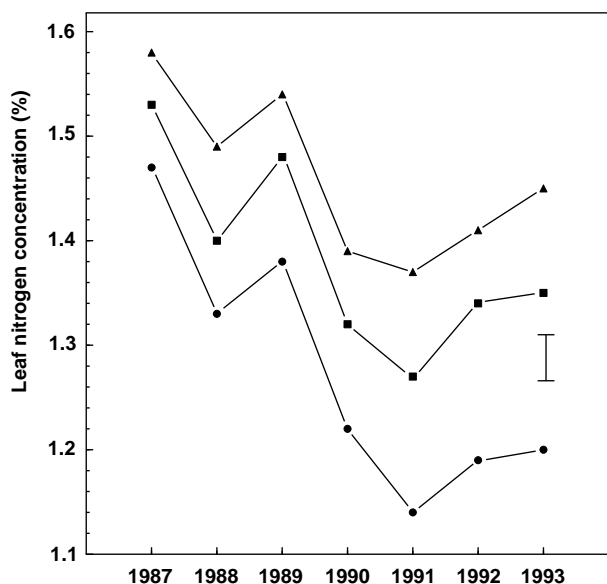
Table 2. Soil analysis at the end of the trial in response to three rates of urea application (0.5, 1.5 and 2.5 kg urea/tree.year) over a six year period

Data are the mean of 20 samples

Means within rows followed by the same letter are not significantly different at $P = 0.05$

Rate of N (g/tree):	230	690	1150
pH (1 : 5 soil:water)	6.6a	6.0b	5.4c
EC (mS/cm)	0.07c	0.08b	0.1a
NO_3-N (mg/kg)	3.2c	7.7b	18.8a
Bicar. extrac. P (mg/kg)	61.0b	69.4a	73.4a
Ca (pH 7.0 meq %)	9.3a	7.8b	6.1c
Mg (meq %)	1.3a	1.0b	0.8c
Na (meq %)	0.09a	0.07ab	0.06b
K (meq %)	0.62a	0.59ab	0.53c
ECEC (meq %)[A]	11.3a	9.5b	7.5c
Extrac. B (mg/kg)	2.1a	2.1a	2.1a
Organic C (%)	2.0a	1.9b	1.8b

[A] Effective cation exchange capacity (Σ exchangeable cations + exchangeable acidity).

range of climatic and cultural data identified rainfall as an important factor associated with yield in this experiment (R. A. Stephenson and E. C. Gallagher unpublished data).

Low N trees producing the highest yields of commercial size nuts had leaf N concentrations of 1.38, 1.22 and 1.14% N in 1989, 1990 and 1991 respectively compared with concentrations varying from 1.37 to 1.58 at the high rate of N (Fig. 3). In 1990 and 1991, N concentrations in low N trees fell at a greater relative rate than those for trees at the intermediate and high rates of N, and subsequent recovery in 1992 and 1993 was slower, presumably due to N removal in nuts in previous years. Allowing leaf concentrations to drop below 1.2% N may be detrimental, in the longer term, to sustained tree health and productivity. A slightly higher plane of N nutrition (e.g. 1 kg urea/tree.year) might be more appropriate in this orchard under the conditions of this experiment. This compares with an estimated 0.6 kg N/tree removed by the crop in this study (50 kg NIS or 67 kg nut-in-husk/tree with 1.5, 0.89 and 0.21% N in kernel, shell and husk respectively; kernels average 30%, shell 45%, and husk 25% of the total weight of nut-in-husk).

Leaf N concentrations fell from a high in 1989, progressively to a low in 1991 (Fig. 3), years in which yields were highest (Fig. 4). It is therefore tempting to speculate that the high yields drew heavily on tree and leaf N reserves during this period. Lower yields in 1992 and 1993 were reflected in a levelling off or slight recovery in leaf N, regardless of the rate of N applied, although the recovery was greater at the high rate of N.

Critical leaf nitrogen

The Hawaiian (Cooil *et al.* 1953) and tentative Australian standard levels for leaf N (Stephenson and

Figure 3. Effect of rate of nitrogen (● 230, ■ 690 and ▲ 1150 g N/tree.year), averaged over 5 application strategies, on N concentration in index leaves of macadamia, cultivar Keaau, in October of each year from 1987 to 1993. Vertical bar indicates l.s.d. value at $P = 0.05$.
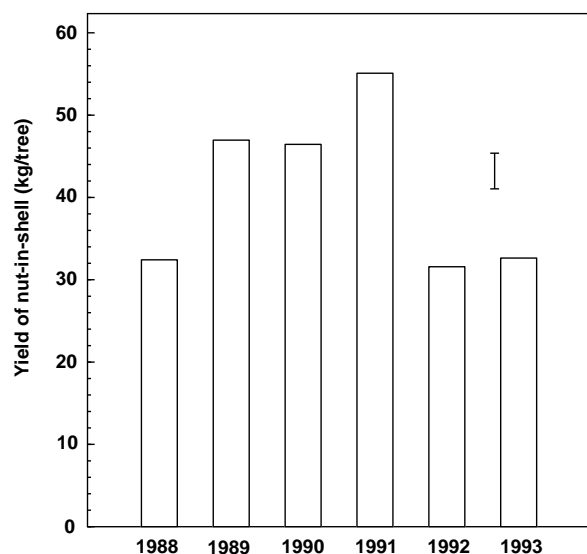
Figure 4. Total yield of nut-in-shell (kg/tree) of macadamia, cultivar Keaau, from 1988 to 1993. Data are the average of 60 trees which received one of 3 rates of nitrogen (230, 690, and 1150 g N/tree.year) applied in one of 5 application strategies. Vertical bar indicates l.s.d. value at $P = 0.05$.

Figure 5. Correlation of yield of nut-in-shell and leaf nitrogen concentration.

Cull 1986) were based on vegetative growth responses and field surveys, respectively. There has not been any rigorous determination of critical leaf N based on tree yield responses. The relationship between leaf N content in October and yield at the subsequent harvest was investigated to better indicate appropriate critical leaf N concentrations for macadamia. In 1993 only, total yield (including intermediate and small, reject nuts) was negatively correlated with leaf N ($r = -0.64$; $P<0.05$). Negative correlations were also obtained for commercially acceptable nuts (>19 mm) in 1991 and 1993 ($r = -0.69$ and -0.77; $P<0.01$, respectively), but not in other years. Other factors had a large impact on yield, thus confounding the possible relationship between leaf N and yield. In the absence of expensive multi-site fertiliser trials over several years, however, this approach provides some confidence for setting a lower critical leaf standard for N.

The significant correlations obtained indicate best yields occurred when leaf N was about 1.3% or less (Fig. 5), well below the tentative standard which was previously adopted (Stephenson and Cull 1986). This result is consistent, however, with the 1.22% leaf N from high yielding macadamia trees (Stephenson and Gallagher 1989*a*). The evidence suggests that concentrations in the range 1.2–1.3% N are satisfactory, at least over the short term. Further studies on the yields of trees since 1994 with lower percentage of leaf N would also be desirable. Furthermore, under Australian
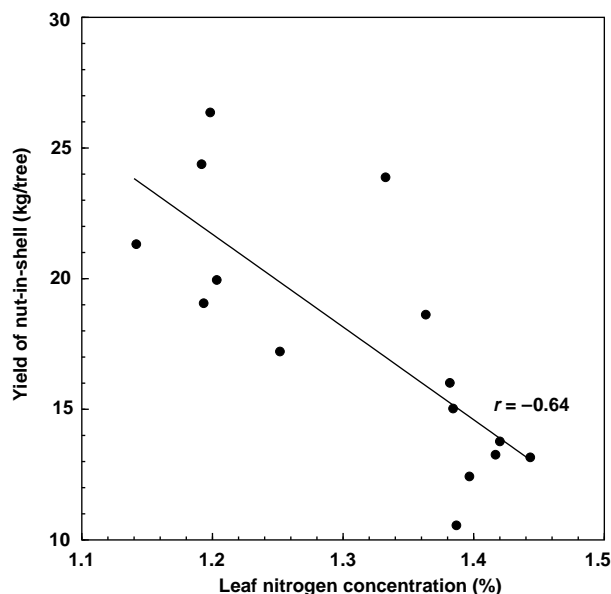
conditions, there have been no data to justify adjusting leaf N status above 1.4%. Thus a conservative new standard of 1.3% N is recommended. These data provide a basis for practical management decisions.

Conclusions

The negative correlation between yield and leaf N suggests that a relatively low plane of N is appropriate for macadamias, perhaps 1 kg urea/tree.year for maximum yields and sustained tree health under conditions similar to those in this experiment. This allows for an estimated 0.6 kg N removed by this level of cropping. Cooil's (1983) estimate of N removal by this level of cropping in Hawaii was about 0.3 kg of N. High yields depleted leaf N, particularly at oil accumulation, indicating demand for N at this stage. It was not possible, however, to identify the critical leaf N level for optimum (90% of maximum) yield, indicating the existence of other yield-limiting factors in this work. Nevertheless, highest yields were obtained when leaf N was 1.2% N. It might be prudent therefore, to adjust the tentative critical leaf N of Stephenson and Cull (1986) from 1.4–1.5% to 1.3% N. In Australia, there is no evidence to support maintaining leaf N above 1.4%. This study also confirms the appropriateness of sampling leaves for nutrient analysis in October as suggested by Stephenson and Cull (1986).

Acknowledgments

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