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# Canopy management for consistent yield in macadamia, 1999

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# Canopy Management for Consistent Yield in Macadamia

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# Chapter 1 Project Details

HORTICULTURAL RESEARCH & DEVELOPMENT CORPORATION

1. Project title: Canopy management for consistent yield in macadamia

HRDC Project No: MC95008

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3. Project Objectives:
   - a) Determine the relationship between canopy structure and yield.
   - b) Assess the potential of leaf based diagnostic tools to indicate levels of shading on grower properties
   - c) Quantify the effects of pruning and tree removal on yield and profitability.
   - d)Collate existing industry information on different canopy management strategies from growers records and replicated trials to develop recommendations for current best practice.

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5. Commence date: 1st July 1995
Anticipated completion date: 30th June 1998

## 6. Project Costs

| Year | Commonwealth contribution ($) | Industry contribution ($) | Total ($) |
|---|---|---|---|
| 1995/96 | 28,895 | 28,895 | 57,790 |
| 1996/97 | 51,171 | 51'171 | 102,341 |
| 1997/98 | 55,712 | 55,712 | 111,293 |
| Total | 71,226 | 71,227 | 271,424 |

# Chapter 2 Summaries and Acknowledgments

## 2.1 Media summary

This study was undertaken due to concerns within the Macadamia industry that yields in high density plantings (<8x5m) will decline with age and it was unclear what was the appropriate management strategy to follow.

The first process in tackling this problem was to determine whether there was a decline due to inter tree competition. To do this intensive investigations of yield response were carried out in orchards at a range of stages of canopy development. Production from 21 sites of cultivar 344 from a range of latitudes was monitored for up to 4 years. Analyses showed that, of several indices of orchard crowding, percentage ground cover (the percentage of the orchard floor covered by canopy) was the best measure for predicting yield.

The project showed that yield decline due to orchard crowding does not occur as early in the life of the orchard as previously expected. :The results indicate that high yields tend to occur in orchards with high percentage ground cover, even up to complete canopy closure. The orchards at this end of the range which did not show any evidence of decline during the project comprised 16 year old trees planted at 7 x 4 m. Previously, Trochoulias (1994) and James (1994) had indicated that yield declined due to overcrowding at year 11 in 5 x 3 m and 7x 4 m plantings respectively.

Yield per ha at the most crowed site showed a significant decline during the project. However because decline occurred at only one site it can not be considered conclusive evidence of yield decline due to crowding. We can not rule out the possibility that some other factor not related to orchard crowding is causing yield decline at that particular site.

Further monitoring of sites is required to identify if and when yield decline occurs. Unfortunately, serious damage was done to the project at the end of the fourth harvest when trees were removed from three key sites. These sites were our most crowded sites after the one that had already shown yield decline. This has left a considerable gap in the range of crowding in the orchards we are monitoring and has probably delayed the opportunity to identify yield decline by several seasons.

The second component of this project was to examine different canopy management techniques to maintain production. Treatments examined included: a light annual hedging to maintain a two meter inter row space; removing every second tree from every second row; and leaving trees untouched. Hedging had no significant effect on yield. Tree removal decreased yield in the first year in which the trees were removed and this significant relative reduction was maintained in the subsequent seasons.

The compiled evidence from grower tree removal trials generally showed reduced yield. In the short term, removal of trees would appear to be a poor option for managing orchard crowding.

Of the alternatives assessed the best method for characterising canopy structure remains measuring the dimensions of trees and inter-row space. Neither leaf nutrient levels nor indirect estimates of leaf area index were able to separate differences in canopy structure as precisely as empirical measures. In testing indirect measurement of leaf area index it was found that mature macadamias have a higher leaf area index than any other commercial horticultural crop.

Detailed study of leaf characters confirmed that leaf age, leaf light environment and leaf nutrient content were affected by shading. These differences were not consistent across sites but were found in all cultivars investigated. Leaf nutrient content of the trial trees at most sites was high compared industry recommendations Yields were also high at the monitored sites and there were no commercially important detrimental effects on nut quality. The use of leaf nutrient content to manage tree nutrition needs revision in view of these results.

## 2.2 Technical summary

This study benchmarked production for macadamia cultivar 344 planted at a range of densities. Orchards used in this study were selected to represent different ages, stages of canopy development and latitudes. Yields and changes to canopy dimensions were recorded for up to 4 successive seasons. At the commencement of this project a number of commercial devices were recently released that were designed to provide objective measures of canopy structure using light sensors. Two of these devices, the LAI 2000 and Ceptometer were examined to determine whether they could be readily used to describe canopy structure in macadamia. The use of leaf characters including nutrient content and specific leaf weight (weight/unit leaf area) at different positions within the canopy were also examined to determine whether these could be used to indicate the level of shading. These measures of leaf nutrient content had the benefit of clarifying whether any of the observed yield differences could be traced to the nutritional status of the orchard.

Anecdotal evidence had suggested that yields would decline as orchards became crowded. To determine the best means of managing potential yield decline a replicated trial was established in which selected blocks of trees had either whole trees removed, or were mechanically hedged, or were left untreated. To supplement these trials, yields from a number of independent grower trials were also compiled.

A total of 21 orchards of 344 were monitored for annual nut-in-shell production for up to 4 years. The tree dimensions measured annually included tree height, canopy width, and skirt height. These were combined with inter-tree planting distance and inter-row planting distances to calculate other canopy indices including percentage ground cover, number of trees per hectare and canopy volume per ha. A series of models were fitted to the data and it was concluded the percentage ground cover was the most important descriptor for nut-in-shell (t/ha) yield. It should be noted that one of the sites with the greatest canopy development had a significant decline (-1.6 t/ha) during this study. However because it was only one site it can not be considered as conclusive evidence of yield decline due to overcrowding.

In the pruning and tree removal trial there was difference in per ha yield between the untreated controls and the mechanically hedged trees. Yield per ha was reduced by 17%, 22% and 18% in successive years in the treatment in which every second tree from every second row was removed compared to the untreated blocks. The pattern of nut drop was modified by tree removal with a greater proportion of the crop being harvested in the first harvests compared to hedging and control treatment. These results contradict the published benefits of tree removal in aging macadamia orchards and suggest yield reductions in the short term. These results were supported by the grower experiences in which yield reductions invariably followed tree removal.

The commercially available devices for indirect estimate of leaf area index tested did not accurately measure canopy structure when there was high levels of ground cover. These instruments were developed to quantify vegetation that had leaf area indices (LAI) of up to 7-8. The LAI of the orchard in which we tested the LAI 2000 had directly measured LAI values of 15-16. These values are among the highest of any vegetation type ever recorded. A correction factor can be used with these devices to give equivalent values but the error associated with this means that it would not be possible to confidently separate orchards with 90-100% ground cover. Therefore, these devices cannot yet be used to replace the physical measure of canopy dimensions and inter-row distance to characterise canopy structure in macadamia orchards.

Leaf based characters were also less effective at predicting canopy cover and yields than physically measuring tree dimensions. Specific leaf weight differed between sites showing that it could not be used across the industry to measure shading. All sites had adequate nutrition but N levels exceeded recently developed recommendations. However, both leaf N and P content did effect yields but P was more important. Due the comparative high yields of trees in this survey compared to previous work and industry averages recommended nutrition should be revised. In relating nutrient status to yield nutrient content as grams/unit leaf area was a better predictor than as percentage of dry weight. Leaf age and shading affected N and P content. As an interim improvement on assessing orchard nutritional status it is suggested that leaves are sampled from the NE side of trees about half way up the canopy. An incidental but important finding from this study is the immediate need to revise recommended measures of tree nutritional status

More conclusive trends are likely by extending the trial for more seasons since the greatest observed variability in these trials was due to differences between years, At this stage it would not appear that yields across the industry are in any danger of dramatic decline. However, these conclusions are restricted to cultivar 344.

## 2.3 Acknowledgments

We thank all the growers that provided access to their properties to monitor 344 production. We thank those industry representatives on the Industry advisory committee, Alan Coates, Kim Jones, John Haaksma John Stock, Rod Thompson and Kim Wilson. Excellent research support was given by Daryl Firth, Russell Priddle, Suanne Richards, Glenn Smith, and Neil Wiltshire. Statistical analyses was also provided by Jeff Wood, Stephen Morris and Bev Gogel. We thank Kim Wilson for acting as project champion. We also thank Neil Treverrow and Nigel Scott for facilitating the productive collaboration between the agencies. Thanks to Angela Gackle for helping to prepare the final report. Appreciation is also extended to the Horticultural Research and Development Corporation and the Australian Macadamia Society for providing funding for the project.

## Chapter 3 Recommendations

### 3.1.1 Relationship between canopy structure and yield

Yield and canopy structure has been monitored at 21 sites representing size age and geographic locations for up to 4 years. Several methods of relating canopy structure to the observed yields have been investigated. Of these methods, the current best descriptor of canopy structure is percentage ground cover. Using this measurement of canopy development there was no conclusive evidence of yield decline as the trees became crowded and no evidence of the substantial (30-60%) decline suggested at the start of the project. Growers should not expect a dramatic decrease in yield, as trees become crowded.

There were large unexplained yield variations due to seasonal and site effects that could in isolation give a grower the impression of decline. The detection of these effects was only possible through the network of monitored sites.

Four years data is insufficient to describe the long-term production of a crop with high seasonal yield variation and a productive life of 30 or more years. The annual and sequential measurement of yield is essential to understanding production changes. Serious damage was done to the project when trees were removed from some of the most crowded sites after the fourth season of monitoring. This has set the project back by approximately three seasons unless new sites with similar crowded plantings can be located.

### 3.1.2 Quantify the effects of pruning and tree removal on yield and profitability.

There were no significant differences in yield between lightly hedged trees and untreated controls. However the removal of every second tree from every second row resulted in an annual reduction of 20% for the three seasons following treatment. Tree removal would therefore seem a poor option. It should be noted that the effects of crowding are not limited to yield and other factors such as erosion, disease build up and orchard access need to be considered. In the short term light annual hedging does maintain a clear alley width for orchard access. However, the longer-term effects and options when the tree height exceeds the capacity of the hedger need to be investigated.

The monitoring of the pruning and thinning trials needs to be extended for at least another 3 years to determine whether there is yield decline due to crowding and to quantify the longer term effects of hedging and tree removal.

### 3.1.3 Collate existing industry information on different canopy management strategies from growers records and replicated trials.

The published results on macadamia canopy management and results from grower trials have been collated and reviewed. The published results suggested a positive yield response to tree removal in Hawaii. In the short term these results were not confirmed by the pruning and tree removal trials that showed a decrease in yield short term. The Hawaiian trials did not contain untreated controls and therefore the response they attributed to tree removal could be explained by seasonal differences.

Most of the Australian grower trials confirmed that there was a yield decrease due to tree removal or pruning. The importance of having control treatments to compare with treated trees was confirmed. Monitoring of grower trials has been beneficial and should be maintained.

### 3.1.4 Assess the potential of leaf based diagnostic tools to indicate levels of shading on grower properties

While lead nitrogen (N) and phosphorus (P) levels are reduced by shading, they can not be used as an index to predict canopy crowding.

Leaf N and P concentrations were also affected by age and cultivar (P). They need to be standardised to reduce leaf sampling error for diagnostic purposes.

Leaf N and P parameters were poorly correlated with yield and we conclude that current leaf N and P standards cannot reliably diagnose the nutritional status of macadamia orchards.

The leaf N concentrations measured across all sites (1.3% -1.8%) which are productive by Australian standards exceeded current diagnostic levels (1.3% - 1.4%) and were not detrimental to yield. As an interim measure fertiliser N rates therefore should be based on crop nutrient removal plus any losses due to leaching.

### 3.1.5 Other objective means of quantifying canopy structure

Macadamia orchards have among the highest levels of light interception of any commercial tree crop. This places the light levels encountered outside the sensitive range of most commercial devices used to measure canopy development. Other options for objectively measuring canopy structure and development based on light levels should be evaluated

### 3.1.6 Seasonal and site effects

We have no explanation for the large year and site effects on yield. The current study indicates that they are independent of canopy structure. Carbohydrate supply, flowering, fruit set and retention are related to final yield. However, it is unclear which are causes and which are effects. If the industry is to have predictable and more stable yields these factors need to be understood and where possible controlled through farm management. Determining the relative importance of the factors that cause yield fluctuations would also assist the setting of research priorities.

### 3.2. Extension/adoption of research outcomes

Preliminary results of this study have already been presented at Annual General Meeting s of the Australian Macadamia Society, AMS Grower field days, joint meetings with the Australian Macadamia Society executive and research providers and submitted to internationally refereed journals.

**Summary of formal Industry Communication 1995-1998**

McFadyen, L.M. (1995) *Canopy Management* .AMS News Bulletin 22(2) pp.9-12

McFadyen, L.M., McConchie, C.A. (1996) *Canopy Management in Macadamia* Challenges for Horticulture in the Tropics, Proceedings of the Third Australian Society of Horticultural Science and First Australian Macadamia Research conference p. 238-243

McFadyen, L.M., Meyers, N., McConchie, C.A., Firth, D., Priddle, R., Richards, S. (1997) *Canopy Management for Consistent Yield in Macadamias* Australian Macadamia Society Conference Report p. 15-19.

Article by Bill Greenhalgh in 'Good Fruit & Vegetables' 1996, based on (2) above, quoting participating agencies and results.

Australian Macadamia Society Field Day, 14 February 1997 - Wollongbar Agric. Institute and Victoria Park orchard.

Huett, D.O. (1998) Leaf sampling considerations for macadamias Australian Macadamia Society Annual General Meeting and Conference, Surfers Paradise, September, pp 28-30

McFadyen, L., Meyers, N., McConchie, C.A., Huett, D. (1998) Canopy Management in Macadamias Australian Macadamia Society Conference Report p.

Australian Macadamia Society Field Day September 1995 – Glasshouse

Project report (1996) in AMS Bulletin 23(1) 7. Canopy management for consistent yields in macadamia

Lisa McFadyen, Noel Meyers and Cameron McConchie spoke at Mac Groups 1997

Meyers, N.M., McFadyen, L.M. and McConchie, C.A. 1997. Optimising canopy structure and yield in macadamia. Presentation to the Australian Macadamia Society southern growers' collective, January 6.

Poster at Wollongbar Agric. Institute Open Day 1998

Meyers N. M., Morris S. C., McFadyen L.M., Huett D. O., and McConchie, C. A. (in press). Investigation of sampling procedures to determine macadamia fruit quality in orchards. Australian Journal of Experimental Agriculture

Meyers, N.M., McFadyen L.M., Huett D.O. and McConchie C.A. (in press). A comparison of direct and indirect estimates of Leaf Area Index of *Macadamia integrifolia* (Maiden and Betcshe). Australian Journal of Experimental Agriculture

Meyers, N. M. , Olesen, T. D. , Morris, S. C. , Richards, S., Huett, D. O. , McFadyen, L. M. , and McConchie C. A. (Accepted for publication subject to revision).The influence of canopy structure on the fruit quality of Macadamia (Proteaceae). Australian Journal of Experimental Agriculture

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### 3.3 Future Research Directions

1. The 344 sites need to be rationalised and monitoring of new 344 trial sites started to supplement the crowded orchards lost to the project. The rationalised sites should still cover a range of environmental conditions and different stages of canopy development.

2. Monitoring of the Rous pruning and thinning trial should be extended to determine the long-term impact of the tree removal and hedging treatments

3. Consideration should be given to starting new pruning trials examining different pruning options such as high skirting and selective limb removal. These trials could use different cultivars.

4.Topworking of poor performing cultivars such as 800 should be trialed as an alternative treatment to tree removal and replanting.

5. Further investigations should be performed to develop objective means to quantify canopy structure to enhance ready transfer of results.

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# Chapter 4

# Literature review:

## Issues in the canopy management of temperate and tropical tree crops.

**4.1 Introduction**: The planting designs and cultivars used for contemporary tree crop orchards bear little resemblance to those planted as recently as 25 years ago. This trend results from planting orchards at higher densities and the selection of smaller trees with shapes conducive to higher productivity (Clayton-Greene, 1993). Higher density plantings have led to earlier interactions between canopies of adjacent trees, associated with declines in both yield and fruit quality in a number of deciduous tree crops.

Extensive research programs have been conducted to optimise orchard designs and canopy management practices to maintain productivity and fruit quality in high-density plantings. These canopy management programs seek to facilitate the efficient conversion of solar radiation into fruit production (Smart and Robinson, 1991). In deciduous crops, such as apple, orchardists generally achieve these objectives using techniques that ensure adequate light penetration into the canopy to secure acceptable fruit quality in the current season and the initiation of sufficient flowers to safeguard fruit production in subsequent seasons (Palmer, 1989). In both apple and grape, relationship has been demonstrated between light availability through the canopy profile and physiological processes, such as; flowering; fruit set; fruit size; fruit colour; and, fruit quality (Jackson, 1980; Lakso, Robinson and Pool, 1989). Optimal light microclimates, resulting in commercially acceptable fruit quality and yield, frequently require manipulation of canopy structure (Palmer, 1989).

This review examines tree crop canopy function and management practices. Previous workers have stressed the important relationship between the orchard light environment and both yield and fruit quality. Hence the relationship between light environment and productivity will form the basis of this review. Researchers frequently use artificial shading experiments to examine the reduction of light availability through a canopy profile. We review several of these experiments to determine the simulated effects of shading on both fruit yield and quality.

Planting designs and management practices influence an orchard's light environment. Some of the factors that we consider include tree planting density and row orientation. Pruning and tree thinning experiments represent one means to manipulate an orchard's light environment. We outline several management methodologies performed in a number of tree crops to improve an orchard's light environment. The review concludes by summarising our knowledge of the functioning and management of tree crops, and suggests areas in which we require additional knowledge in macadamia before further advances can be made.

We begin by focusing on the differences between tree crops grown in temperate and tropical regions of the world.

### 4.2 Tree crops: a historical perspective.

Records of the domestication and cultivation of apple and pear occur from over 2500 years ago, with suggestions that cultivation may have occurred in prehistoric times (Brown, 1975; Layne and Quamme, 1975). Considerable knowledge has accumulated relating to these deciduous, temperate tree crops. In comparison, research into the productivity of tropical, evergreen tree crops is recent, with commensurately less accumulated knowledge available.

### 4.3 Deciduous versus evergreen canopy function.

The growth and physiology of temperate tree crops reflect the environments in which they evolved (Colinvaux, 1993). The deciduous[1] habit of apples may well have evolved in response to summer temperatures of 30°C and winter temperatures 43°C below zero (Brown, 1975). Examples of deciduous temperate tree crops include: apple; almond; chestnut; citrus; hazelnut; pear; pecan; pistachio; and walnut.

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[1] Describing woody, perennial plants that shed their leaves before the winter or dry season. Leaf fall is an adaptation that reduces water loss when little or no water is available to a plant's roots ( Blackmore, 1988).

Examples of evergreen[2] tropical tree-crops include: macadamia; avocado; cashew; fig; lychee; longan; mango; mangosteen; and rambutan. Evolution of the evergreen habit may have occurred in response to smaller differences in temperature between mild winter and summer temperatures (Colinvaux, 1993).

Divergences in the physiology of deciduous and evergreen species, include differences in: resource allocation to growth and reproduction (Tobanen and Laine, 1997); photosynthetic capacity and leaf productivity (Prado and Demoraes, 1997); nutrient assimilation, storage, cycling and partitioning within the plant (Sobrado and Ehieringer, 1997; Knops and Koenig, 1997). Hence, suitable canopy management strategies for these physiological processes could differ between deciduous and evergreen tree crops.

Palmer (1989) suggests that the canopy light environment of trees and orchards should be maximised in both deciduous and evergreen tree crops to maximise the potential productivity. Therefore, to begin, we consider the light environment and canopy functions of individual trees.

### 4.4 Light environment and productivity of individual trees

Leaves primarily function to harvest light and carbon dioxide ($CO_2$) and convert these resources into carbohydrates via photosynthesis (Raven et al., 1986). Many studies have examined photosynthesis of individual leaves within forest canopies. However plant canopies comprise many leaves, therefore, extending leaf-based understandings of photosynthesis and assimilation processes to whole canopies requires the consideration of the collective properties of these leaves (Hollinger, 1992; Holbrook and Lund, 1995). Any attempt to synthesise our understanding of canopy assimilation should account for variation in photosynthetic rates of individual leaves due to differences in: light intensity (Doley et al., 1988); capacity to harvest and fix $CO_2$ (Pearcy, 1987; 1990; Hollinger 1992); and, capacity to support water loss inherent in $CO_2$ uptake (Holbrook and Lund, 1995; Yates and Hutley, 1995; Hutley et al., 1997).

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[2] A woody perennial plant that retains its foliage throughout the year by continuously shedding and replacing a few leaves at a time. Many evergreens are tropical or equatorial in distribution, and are not subjected to long periods of

Differences in canopy form will not only influence the quantity of photosynthetically active radiation (PAR) intercepted, but will also influence canopy function (Porter, 1989). For example, leaves high in a rainforest tree's canopy exhibit higher light saturated photosynthesis rates and light compensation points[3] compared with leaves located farther down the canopy (Holbrook and Lund, 1995). Typical light compensation points of rainforest canopy species are c.1-2% of full sunlight (Salisbury and Ross, 1985; Doley et al., 1988; Barker et al., 1997). *Macadamia integrifolia* seedlings, by contrast, have light compensation points of c.10% of full sunlight (Broomhall, 1988). Several shade-intolerant rainforest species, such as Sassafras and Beech, share *M. integrifolia*'s high light compensation point (Read and Hill, 1985; Read and Bushby, 1990). In contrast to wide spacings occurring between shade-intolerant individuals in rainforest communities (Bale and Williams, 1994; Hosking et al., 1993; Read et al., 1995), increasing planting densities in commercial tree crop orchards result in significant levels of mutual shading in adjacent trees (Palmer, 1989). The responses of shade intolerant species, such as macadamia, to increased levels of shading have rarely been documented (O'Brien and McConchie, 1995).

## 4.5 Orchard light environment and productivity

Plant growth rates are often proportional to the amount of radiation intercepted by the canopy (Russell et al., 1989). Frequently horticultural crop yield is considered on the basis of light intercepted by the canopy. Researchers have demonstrated a linear relationship exists between orchard productivity and light interception[4] in numerous woody crops (Table 4.1). Several studies indicate that reductions in fruit quality occur as shading reduces light availability through the canopy profile (Table 4.2). Reduced light transmission through the canopy also results in detrimental effects on both quality and yield factors in several tree crops, in particular in apple (Ferree, 1980; Heinicke, 1964; 1966; Morgan et al., 1980; Myers and Ferree, 1983a; 1983b). For example, an individual apple can vary significantly in color, size, and quality depending on the position in which fruit are borne within the canopy (Jackson, 1970).

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winter cold, or dry seasons (Blackmore, 1988).

[3] Light compensation point: point at which photosynthesis balances respiration (Net $CO_2$ exchange = 0).

[4] Light interception represents the difference between the light transmitted through the canopy and the light measured above the canopy (Jackson and Palmer, 1977).

**Table 4.1.** Tree crops exhibiting a linear relationship between light interception and fruit production.

| Crop | Source |
|---|---|
| Apple | Palmer and Jackson, 1977; Byers et al., 1985; Hunter and Proctor, 1986; Flore and Lakso, 1989; Palmer, 1989; Robinson and Lakso, 1989; Byers et al., 1990a; Palmer et al., 1992. |
| Red raspberry | Palmer, Jackson and Ferree, 1987 |
| Mandarin | Tachibana and Nakai, 1989 |
| Sweet cherry | Flore and Lakso, 1989 |
| Sour cherry | Flore and Layne, 1990 |
| Pear | Khemira et al., 1993 |
| Peach | Byers et al., 1985; Byers et al., 1990b |
| Grape | Miller, 1982; Palmer, 1989 |

**Table 4.2.** Tree crops found to produce poorer quality fruit in response to increased levels of canopy shading.

| Crop | Source |
|---|---|
| Apple | Jackson, 1977 |
| Mandarin | Iwagaki, 1981 |
| Sour cherry | Flore and Sams, 1986 |
| Red raspberry | Wright and Waster, 1984 |
| Macadamia | Stephenson and Trouchoulias, 1984 |

Apple branches receiving less than 30% full sun have been shown to set no fruit (Heinicke, 1964), while the main fruiting zone occurs in the periphery of the canopy, where light levels of between 30 and 95% full sunlight occur (Jackson, 1970; Verheij and Verwer, 1972; 1973). The fruiting zones of the canopy of "Shamouti" orange correspond to areas characterised by net positive photosynthesis (Cohen and Fuchs, 1987; Cohen et al., 1987). Both apple and citrus therefore transport the products of photosynthesis over short distances from well illuminated leaves compared with evergreen crops such as macadamia. Macadamia, in contrast, exhibits the capacity to transport assimilates over significant distances from the site of production (Trueman and Turnbull, 1994b; O'Brien and McConchie, 1995). However high levels of shading result in significant reductions in kernel oil content and lower levels of fruit set (O'Brien and McConchie, 1995).

Palmer and Jackson (1974) found that production in young high-density apple orchards increased as light interception increased between 20 and 60% of full sunlight. Verheij & Verwer (1973) measured light interception of apple canopies in a spacing trial and found that the highest yields occurred in orchards achieving 70% light interception (Verhei and Verwer, 1972; 1973). At interception levels of between 60% and 80% of full sunlight a sharp decline in yield occurred (Verheij and Verwer, 1972; 1973; Wertheim et al., 1986; Lakso, 1994). This result indicates that mutual shading of adjacent canopies significantly reduces the potential for net positive photosynthesis below levels capable of supporting the crop. In combination, these results emphasise the importance of light distribution through the canopy.

Differences in canopy architecture, tree planting density and row orientation influence the quantity of photosynthetically active radiation (PAR) intercepted by individual leaves and whole canopies and the spectral quality of light filtering to lower levels of the canopy (Porter, 1989). Changes in light quality interact with several physiological parameters, discussed below.

### **4.5.1** *Light quantity, quality and shading*

Light quantity and quality together describe the light environment of any portion of a tree's canopy. Light quantity comprises irradiance contributions from sunflecks, transmitted, reflected and diffuse skylight (Palmer, 1977a; 1977b). Light quality refers to the availability of particular wavelengths of light in the photosynthetically active portion of the spectrum (Ferree et al., 1993). Frequently a strong relationship exists between changes in light quality and quantity within canopies. This correlation makes separation of the influence of each factor experimentally difficult (Lakso, 1994).

Marked reductions in blue and red wavelengths and a shift in the red: far-red[5] ratio characterises declining light quality at increasing depths within the canopy (Palmer, 1977; Gratani, 1997). Decreases in the red: far red ratio through the canopy profile result from low levels of transmission of red light compared to that of the infra-red (Palmer, 1977a; 1977b). Reduced levels of red wavelengths at increasing depths within the canopy have the potential to significantly alter the photosynthetic capacity of leaves as some of these wavelengths are required for the photosynthetic action spectrum[5] (Salisbury and Ross, 1985).

Differences in the red: far-red ratio can significantly alter tree development and physiology (Raven et al., 1986). For example, using different red: far red ratios (at the same level of irradiance) resulted in significant delays in bud break and reduced branching frequency in "Redhaven" peach (Erez and Kadman-Zahavi, 1972). While delayed apple fruit abscission occurs following exposure to short periods of red light during the night (Greene et al., 1986).

The influence of changes in light quality through an orchard canopy on both floral initiation and fruit retention have not been extensively studied in tree crops. This area provides significant scope for future research.

### **4.5.2** *Effects of shading on flower and fruit production and fruit quality.*

"Characterisation of the light environment [both quantity and quality] of a particular leaf, or portion of the canopy that relies on artificial shading under natural light conditions vastly oversimplifies the complexity of the natural light environment in tree

---

4 The ratio of irradiance measured at wavelengths 660nm and 730nm.

[5] The action spectrum of leaves defines the relative effectiveness of different wavelengths of photosynthetically active radiation for light requiring processes, such as photosynthesis and floral induction (Blackmore, 1988).

canopies" (DeJong and Doyle, 1985). Artificial shading experiments, however, allow preliminary experimental analysis of the physiological responses associated with decreased light availability within a canopy. These experiments have demonstrated that orchard productivity is limited by light availability, orchard/tree planting density and canopy structure (Palmer, 1989; Jackson and Palmer, 1977). Experiments that apply artificial shading to apple canopies have resulted in significant declines in orchard and tree yields. Such work reveals a complex relationship between the levels of shading in the current year and tree crop yields borne in the previous year (Jackson and Palmer, 1977). Shading may also affect yields by influencing several physiological processes including: floral initiation; fruit set; fruit development; photosynthesis; and, carbohydrate partitioning and storage.

The relationship between light interception and productivity may not necessarily be linear. For example, reductions in light interception by apple branches did not detrimentally influence apple floral initiation, until light availability declined below 65% of full sunlight (Cain, 1971; 1972; Khemira, 1993). Shading to 37% of full sunlight in the apple cultivar "Cox's Orange Pippin" from early June until leaf fall resulted in a 36% reduction in the number of spur buds, with a greater decline in axillary and terminal bud formation (Jackson and Palmer, 1977). Shading from bud formation until harvest resulted in a 62% reduction in "Delicious" apple fruit set and resulted in depressed yields in the following year (Doud and Ferree, 1980). Highest levels of fruit set and fruit size generally occur in the upper portions of apple canopies, compared with the lower, increasingly shaded portions of the canopy (Doud and Ferree, 1980; Justin et al., 1988).

Stephenson and Trochoulias (1994) report that shading young potted macadamia trees reduced flowering, nut numbers, kernel recovery and oil content. However experimental methods and results were not provided. Artificially shading the sides of mature macadamia trees produced declines in Nut-In-Shell (NIS) yields (Liang and Myers 1978).

Artificial shading experiments in apple result in significant depression of initial fruit set and yields following prolonged shade (Doud and Ferree, 1980; Lehman et al., 1987).

However, fruit production in tree crops represents a function of initial-fruit-set and fruit retention following pollination (McConchie et al., 1997; Sedgley and Griffin, 1989). Early work in apple identified the first major fruit abscission period to occur approximately 15 days after bloom and continue for up to 14 days (Luckwill, 1953). Researchers initially ascribed early floral abscission to poor pollination and fertilisation. Subsequent artificial shading studies determined short periods of shade influenced apple fruit abscission (Byers et al., 1985; Byers et al., 1990a; 1990b; Byers et al., 1991; Polmonski et al., 1988). Periods of shading as short as three days could reduce viable fruit retention from 87% to 17% in "Redspur Delicious" apples up to 30 days post-bloom (Byers et al., 1991). These studies conclude that inhibition of current photosynthesis primarily contributes to early fruit abscission. Byers et al. (1991) speculate that reduced assimilate production results in greater ethylene production during critical phases of apple fruit resource demand, which causes enhanced fruit abscission. Shading during the first month after apple flower bloom influences the number of fruits set and the rates of cell division which ultimately determine fruit size (Byers et al., 1990; Lakso, 1989, Corelli-Grappadelli and Coston, 1992).

Significantly greater fruit size occurs in the apple cv. "Granny Smith" in the well-illuminated outer portions of the canopy, compared with the shaded inner canopy (Justin et al., 1988). These authors also report a strong interaction between position in the canopy and orientation of fruiting branches that significantly influence fresh fruit weight and total soluble solid concentration of fruit. Upright "Granny Smith" branches generally support greater numbers of better quality fruit than branches exhibiting a more pendant habit. However, optimum branching angles for light distribution to fruiting spurs in apples awaits determination.

Attempts to define the period during which shading critically influences fruit development produce variable results, perhaps due to the experimental designs utilised and the comparisons considered. For example, 26 year old "Starkrimson" apple trees shaded from 10 to 26 days after bloom abscised considerably fewer fruit compared with younger "Redchief' trees shaded for the same period of time (Byers et al., 1985).

These shading studies applied a photosynthetic inhibitor to trees, or enclosed trees in neutral density shade cloth. The cloths reduced incident light levels to 8% of full sunlight at the top of the canopy (Byers et al., 1991). This level of illumination may be insufficient to support the developing crop (Verheij, 1970), hence reductions in crop loads may occur to match available resources (Trueman and Turnbull, 1994a) at the time of artificial shade applications.

The light environment in which leaves initiate and develop mediates the photosynthetic capacity of individual leaves (Barden, 1974; Kappel and Flore, 1983; Marini and Marini, 1983). Generally leaves grown in highly illuminated portions of the canopy exhibit significantly higher light compensation points and saturated photosynthetic levels when compared with leaves that initiate and grow in light depauperate regions of the canopy (Boardman, 1977; Chabot and Chabot, 1977). Variations in leaf photosynthetic capacity have been ascribed to differences in chlorophyll and protein content (Boardman, 1977; Kappel and Flore, 1983; Marini and Marini, 1983) or leaf anatomy or physiology (Barden, 1974; Gulman and Chu, 1981; McMillen and McClendon, 1983). Experiments that shade whole trees do not duplicate the light environments experienced within canopies of orchard trees. Such experiments result in reduced irradiance throughout the canopy, instead of the application of uniform levels of shading to all portions of the canopy. These experiments therefore reinforce the differences in physiology, anatomy and photosynthetic capacity resulting from the conditions in which leaf and branch initiation occurs.

From the experiments described a series of factors remain unresolved. Generally researchers accept that those older branches, located in the lower portion of the canopy, produce fewer flowers and/or set less fruit due to a depauperate light environment, or reduced light quality. However, few experiments attempt to separate these factors because they vary linearly with each other (Lakso, 1994). It remains unclear whether older branches when exposed to high light environments, such as occurs after pruning or thinning of trees, , produce equivalent numbers of flowers and fruits compared with younger branches receiving the same level of irradiance. Experiments comparing equivalent levels of shading and different light qualities throughout the canopy would answer these questions. Few experiments attempt to examine resource allocation to fruit production and physiological processes throughout the canopy in response to localised changes in the light environment. However, experiments conducted along these lines offer the possibility of an enhanced understanding of the cropping process.

Researchers still debate the relative importance of the duration of shading on fruit set and development and their interactions with the following factors: pruning and training system and hence light availability (Palmer and Jackson, 1977; Wunsche et al., 1993); cultivar (Palmer, 1989); poor pollination and fertilisation (Luckman, 1953); inter-shoot resource competition (Quinlan and Preston, 1971); tree age and storage carbohydrate effects (Stephenson et al., 1989); orchard design (Khemira, 1993); or season.

Orchard design and management issues could alleviate the detrimental effects associated with inter and intra-tree shading. We consider several of these factors on orchard light interception below.

## 4.6 Orchard design factors which influence orchard and tree light interception

Light interception and light quality in mature orchards represent a function of several factors, including: row orientation; tree spacing; tree height; clear alley width ratio; tree shape; Leaf Area Index (LAI) within the canopy; location and age of wood where flowers and fruit initiate and set; training system; and, pruning strategy (Verheij and Viewer, 1972; Ferree, 1980; Ferree and Hall, 1980; Kappel et al., 1983; Porpigilia, 1981; Rom et al., 1984; Rom, 1991; Khemira, 1993; Robinson, Lakso and Ren, 1989).

### 4.6.1 *Row orientation*

Few studies consider the influence of row orientation on light interception and yield in the tropical and sub-tropical regions. Predominantly, researchers determine optimised row orientations by modelling orchard light interception (Cain, 1972; Jackson, 1980). Modelling light interception in different row orientations requires several simplifying assumptions - that: canopies represent non-transmitting solid objects (Mutsaers, 1980); canopies within an orchard row form a single, symetrical object (Palmer and Jackson, 1977); or that light attenuation declines logarithmically with respect to the area of leaves in the canopy (Palmer and Jackson, 1977). Modelling approaches often produce poor correlations between measured and predicted light interception within canopies over periods of hours, days or years (West and Wells, 1992). Frequently, these correlations are used to predict wood biomass accumulation in forestry systems (West, 1993). However, few studies attempt to predict fruit yield from light interception due to the complexity of the modelling required. Instead, due to the strong relationship between light interception and yield demonstrated in several deciduous tree crops, researchers use models to identify orchard designs that optimise light interception and make the assumption that yield increments will follow.

Numerical modelling approaches indicate the greatest effects of row orientation on daily irradiance absorption occur at latitudes of approximately $25^0$ north or south (Mutsaers, 1980). At high latitudes up to $55^0$ N or S, these models predict that greatest absorption occurs in N-S rows in summer, and in E-W rows for the rest of the year (Cain, 1972; Jackson and Palmer, 1977; Mutsaers, 1980). Mutsaers (1980) predicted that trees planted in E-W rows and N-S rows receive the greatest interception at latitudes greater than $65^0$ and near the equator respectively. However, theoretical calculations suggest that the southern side of trees planted in E-W rows would receive almost full illumination outside summer months while the north sides would remain almost totally shaded at latitude $43^0$ N (Cain, 1972; Jackson and Palmer, 1972). We could not find any studies that examined the relationship between heavily shaded sides of the canopy and yield. However, reductions in floral induction, fruit set and fruit yield occur in several deciduous tree crops as shading increases through the canopy profile (Heinicke, 1964; 1966; Morgan et al., 1980; Myers and Ferree, 1983a; 1983b; Palmer, 1989). Moss et al. (1972) determined that leaves located proximately to apple fruit exclusively supplied assimilates to support fruit development. The dependence between fruit numbers and the availability of early season irradiance in apple has also been shown (Lakso, 1994). In combination these studies indicate limited assimilate mobility could occur from the illuminated portion of the canopy to the shaded portion to support fruit development. No studies cited by these authors have examined the contribution of shading different sides of the canopy.

Without considerable assimilate translocation from the illuminated portion of the canopy or from storage reserves, or enhanced assimilation in the illuminated portion of the tree, poor yields could be expected to occur in high latitude E-W rows.

Cohen et al. (1987) modelled light interception of different row shapes and orientations in “Shamouti Orange” and assessed their influence on both photosynthesis and transpiration. This model suggested that row orientation had little effect on estimated photosynthesis for the orchard, however, it was noted that N-S row orientations allowed greater light penetration into canopies if row spacing incorporated a wide inter-row alley.

Small yield increments due to increased orchard interception may not solely influence decisions of row orientation. Other factors, such as fruit quality may also influence the choice of row orientation. Jackson and Palmer (1972) found that although greater light interception occurred in E-W rows at $52^0$ N in apples, they recommended N-S rows. They made this recommendation to facilitate equitable light distribution within the apple canopy; thus ensuring enhanced fruit quality.

Lombard and Westwood (1977) described yield increases of 34% and 48% in N-S rows for "William" and "Anjou" pears respectively when compared with E-W rows planted at latitude $42^0$ N. They measured increased flowering density in N-S rows compared with E-W rows, with equivalent fruit sets per inflorescence in both orientations. This results in higher yields in N-S rows than E-W. Christiansen (1979) observed a 15% increase in fruit yield of "Spartan" and "James Grieve" apples when planted in N-S compared to E-W rows at latitude $55^O$N. Similarly, “Anjou pear” produced a cumulative yield increment of 19% between 1974 and 1991 in N-S rows at latitude $42^O$N (Khemira, 1993). In all cases, significantly greater fruit fresh weight occurred in E-W rows compared with N-S. This result indicates N-S rows produced greater numbers of smaller “Anjou pear” fruit compared with E-W rows.

The relevance of modelled light interception studies from high-latitude deciduous orchards to low-latitude evergreen species awaits determination. While Broomhall (1987; 1988) investigated light interception of different macadamia tree spacings, no investigation into effect of row orientation on canopy light environment occurred. While tree height, row spacing and row orientation influenced the level of mutual shading in pine forestry systems (Verbyla and Fisher, 1989), we found no similar studies in evergreen tree crops. Further studies are required to determine whether yield increments of evergreen tree crops occur in response to row orientation and/or light distribution within the canopy.

### **4.6.2** *Tree planting density influence on yield*

Higher tree planting densities have become an increasingly popular orchard design strategy in many horticultural and forestry tree crops. Optimum apple planting densities, conclude Palmer and Jackson (1974), occur when the cropping zone receives adequate light for floral initiation, fruit maturation and fruit color development in apple. Other researchers use this paradigm as the basis of their attempts to optimise orchard planting density.

Several studies compare tree yields in density trials, frequently from disparate planting densities. These studies demonstrate that tree-planting density primarily influence orchard yields (Wertheim, 1986; Palmer, 1988; Robinson and Lakso, 1989; Clayton-Greene, 1993). Published reports suggest considerable variation in response to planting density; for example apple yields did not necessarily increase linearly with planting density (Clayton-Greene, 1993). Palmer (1989) ascribes such non-linear responses as planting density increases to excessive mutual shading of adjacent trees.

A trial based on the Nelder wheel design (Nelder, 1962) has been performed in South Africa using macadamia cv Nelmac 2 (Oosthuizen, 1992). This trial design design allows simulatneous investigation of the effects of a number of planting densities on yield. In this trial trees were established along a series of radiating spokes with a common origin or vertex (Oosthuizen, 1992). Trees planted at the same distance along each of the spokes represent particular planting densities. Those trees planted at the base of the spokes represented the highest planting densities (5 X 5 m or 400 trees ha$^{-1}$ while those planted at the ends of the spokes represented the lowest densities (15.7 X 15.7 m or 41 trees ha$^{-1}$) For statistical purposes each tree within a spoke was treated as an individual replicate. Estimates of yields per hectare for each of the different planting densities were derived from mean tree yields at that density multiplied by the planting density. Tree densities in the macadamia planting density trial were highest in the first, and lowest in the last row.

Yields were measured from nine to 19 years after establishment. Despite a maximum planting density of 400 trees per hectare in the border row, Oosthuzian (1992) extrapolated the yield response to planting densities of 550 trees per hectare. Yields in years nine to 12 increased linearly over all planting densities. From years 14 to 19 following establishment Oosthuzian (1992) indicated yield decline at 550 trees ha$^{-1}$ in all but two years. Planting densities that consistently produced the highest yields varied between 200 and 300 trees ha$^{-1}$. The maximum productivity of Nut-in-Shell (NIS) kg ha$^{-1}$ varied over these years between three and seven tonnes. Oosthuzian did not provide measures of the nut-in-shell moisture content of these yields. Hence we cannot readily compare these yields with data collected elsewhere. While the relationship between yield and tree planting density are described in these studies, no indications are given of the effects of plant density on fruit quality. Without this information we cannot assess the influence of tree density on factors such as kernel recovery or 1st grade kernel for macadamia.

Macadamia cultivars exhibit considerable variation in canopy characteristics (Stephenson et al., 1993) so different cultivars may be better suited to specific planting densities. Futher studies are needed to determined how different cultivars respond to varying planting densities.

The Nelder wheel, or a rectilinear design operating on the same principle (Verheij, 1970) have also be used to assess the effects of planting density on yield of apple (Christiansen, 1979). Christiansen (1979) describes the yield relationship of apple trees planted at densities between 100 and 40 000 trees ha$^{-1}$ over eight years. "Spartan" and "James Grieve" apple cultivars were each trialed on two different rootstocks. Both cultivars produced the highest yield ha$^{-1}$ in the second and third year after planting. Tree removal occurred from the centre of the planting in the fourth year to allow orchard management practises. "Spartan" yields declined between years six to eight (final sampling year), while yields of "James Grieve" had plateaued at densities of 10 000 trees ha$^{-1}$. We can only speculate whether yields would continue to decline in "Spartan", or show a significant reduction at high planting densities of "James Grieve" after year eight.

In all eight years of Christiansen's (1979) study, individual tree yields of both apple cultivars significantly declined when compared with trees planted at lower densities. At the highest planting densities of 12 700 trees ha$^{-1}$, yields from individual "Spartan" trees significantly declined in years 4, 6, 7 and 8 below those recorded in the third year. At the highest planting density, yields of "James Grieve" did not increase beyond the levels achieved in year four. In combination these results indicate the strong interaction between cultivar and very high planting density on orchard and tree yields.

High-density apple bed planting systems can achieve canopy closure in less than two years (Palmer and Jackson, 1977). Verheij and Verwer (1973) noted at lower planting densities that maximum fruit production frequently occurs before full canopy closure. Canopy closure results in higher leaf densities and reduced illumination throughout the canopy profile (Cohen et al., 1987). Increased levels of canopy shading at higher planting densities decrease apple fruit dry weight accumulation and fruit quality factors such as: apple skin color (Wagenmakers and Callesen, 1995; Clayton-Greene, 1993); soluble solids and firmness (Doud and Feree, 1980; Heinicke, 1966; Robinson et al., 1983); and fruit weight (Palmer et al, 1992; Wagenmakers and Callesen, 1995). Decreases in apple fruit weight at higher density plantings may result from reductions in carbohydrate supply to fruits (Stuart Tustin et al., 1992; Wagenmakers, 1988), or higher fruit densities per unit canopy area (Wagenmakers and Callesen, 1995). Reduced firmness and total concentrations of soluble solids apparent in fruit derived from trees planted at high densities suggests that high levels of canopy shading not only interfere with assimilation, but with partitioning of assimilates to developing fruits.

Reduced light penetration occurred in macadamia canopies which had closed over the inter-row alley due to high planting densities, compared with open macadamia canopies planted at lower densities (Broomhall, 1987; 1988). Broomhall (1987) further suggested an association between reduced light penetration and proportionally fewer branches producing nuts in the closed canopies. Oosthuzian (1992) also observed that the macadamia crop tended to be borne in the upper half of the trees planted at higher densities. O'Brien and McConchie (1995) experimentally confirmed these observations in cultivars 344 and 660. These results suggest that increasing levels of canopy shading detrimentally influences leaf and fruit production in closely spaced macadamia orchards. It remains unclear whether there is a detrimental effect of inter tree shading on total productivity of a macadamia orchard.

The influences of tree planting density, stage of canopy development for tropical evergreen tree crops suggest significant increments in yield could occur following the optimisation of these management practices. However declining light quality and quantity through the canopy profile with increasing planting density may not be the only limiting factor that influences yield and fruit quality. Exploitation of the soil profile by a plant's root system is also influenced by tree planting density, which may likewise influence yield. Below we consider the effects of tree planting densities on root development.

### **4.6.3** *Tree planting density influences root development*

Tree planting densities influence the formation and location of root formation and exploitation of the soil profile. In widely spaced apple and citrus orchards Atkinson (1976; 1978; 1980) and Atkinson et al. (1976) report the tree's root system predominantly comprises horizontal roots. These roots leave large quantities of the soil volume un-exploited. The roots of individual apple trees exhibited greater root density and exploitation of the soil volume as planting density increased. As citrus planting densities increases, the above ground biomass decreases (Chalmers et al., 1981), with comparable reductions in root biomass per plant (Atkinson, 1976; 1978) resulting in the maintenance of root: shoot ratios. We consider below, the root: shoot ratio and methods to describe and maintain productive canopies by manipulating the light environment.

### **4.6.4** *Canopy Leaf Area Index*

A strong relationship exists between light interception and Leaf-Area-Index (LAI)[6] and the arrangement of LAI in space (Palmer, 1980). Palmer and Jackson (1977) concluded that LAI was the single largest factor determining light interception in discontinuous canopies. However, few studies examine this relationship, probably because of the laborious methodology involved.

Numerous computer models (Palmer et al. 1987; Charles-Edwards and Thorpe 1976; Jackson and Palmer, 1979; 1980; 1981; Palmer, 1977; 1980; Palmer and Jackson 1977; Cain 1972) investigate the effects of LAI, tree height, shape and tree spacing on light interception. Good agreement exists between some of these models and field observations but the work has not yet been extended to many other horticultural crops besides apple. Nor has an optimum arrangement of LAI in three dimensions been related to yield. Pruning rearranges the distribution of leaves in space. Several studies related tree pruning to changes in fruit production and quality. Below we consider the physiological basis for pruning and its influence on tree structure, light environment, yield and fruit quality.

### **4.6.5** *Tree Pruning*

Closely planted orchards of small statured trees exhibit a greater capacity to intercept light than orchards composed of widely spaced, larger trees (Jackson, 1970; 1980; Jackson and Palmer, 1980). Limb, root and canopy pruning techniques offer one management tool to maintain canopies in a condition which facilitates optimal light interception in closely spaced orchards. Several pruning techniques improve an orchard's light distribution, to ensure optimal photosynthesis and resource allocation to large numbers of high quality fruit (Heinicke, 1963; 1964; 1966; Jackson, 1970; 1980; Jackson and Palmer, 1980; Smart and Robinson, 1991). The majority of pruning literature investigates the response of deciduous crops to pruning, while comparatively few studies examine the responses of evergreen canopies to pruning.

Many pruning experiments examine both tree and orchard responses to pruning in terms of: canopy growth; floral initiation; fruit set; fruit yield; fruit size; and, fruit quality. Comparitively fewer studies examine the influence of pruning on canopy physiology processes such as: photosynthesis; respiration; or, assimilate mobility within the

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[6] LAI represents the area of leaf above a unit area of ground.

canopy. We have summarised the experience derived from deciduous pruning strategies below, and examine several specific studies of relevance to macadamia.

### **4.6.6** *Physiological basis of the pruning response*

Pruning is routinely carried out in many tree crops to improve the light environment within orchard trees (Mika, 1986). Plant hormones mediate responses to pruning, and control many aspects of plant growth and development (Salisbury and Ross, 1986; Moore, 1989). Auxins represent one group of plant hormones we will consider in detail. Auxin[7] production occurs in the growing apical tips of shoots (Raven et al., 1986). Auxins produce an inhibitory effect on lateral, or auxiliary shoots (Salisbury and Ross, 1985), a process known as apical dominance. Removal of the auxin producing apical tips releases nearby shoots from the inhibitory effects of apical dominance (Kramer and Kozlowski, 1979). The release results in rapid growth of adjacent shoots that significantly increase the dimensions of vascular connections (Salisbury and Ross, 1985). As a result, shoots monopolise nutrients from the roots and stored carbohydrates from the main stem. Consequently growth suppression occurs in surrounding shoots once auxin production occurs in sufficient quantities to re-establish apical dominance.

Artificial removal of the shoot apex can release lateral shoots from apical dominance and results in reduced photosynthesis, and accumulation of assimilates in shoots and leaves (Mika, 1986). Pruning may change the total dry weight partitioning in favour of biomass allocation to new shoots at the expense of the rest of the plant (Mika et al., 1983).

Plants are believed to function via a series of complex feedback mechanisms operating between canopy and roots (Kramer and Kozlowski, 1979). One of these interactions represents a "functional equilibrium" in the root: shoot ratio, which responds to change by adjustment and maintenance (Brouer and DeWitt, 1969).

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[7] Auxins represent a group of plant growth substances whose principle effects are brought about by their capacity to promote the elongation of shoots and roots when present in low concentrations. The inhibition of growth at higher auxin concentrations may be due to the auxin-promoted synthesis of ethylene, which inhibits cell elongation. Organ abscission has frequently been associated with low levels of auxin, and auxins have thus been used to prevent pre-mature fruit drop (Blackmore, 1988).

Each species is thought to have a characteristic root: shoot ratio which remains constant in a stable environment (Kozlowski and Pallardy, 1997). It is possible to characterise several of the physiological changes occurring resulting from changes in the root: shoot ratio below.

### **4.6.7** *Root pruning*

Root pruning has been found to result in dwarfed trees in apples (Maggs, 1965; Faust, 1980); citrus (Alexander and Maggs, 1971; Castle, 1983); and peach (Richardson and Row, 1977). For example, root pruned apples exhibited 32% reduced tree yields compared with untreated controls (Ferree, 1976). A reduction in apple shoot growth, following root pruning, may continue for up to three years following treatment.

Reducing the area of roots in contact with the soil reduces water availability (Raven et al, 1986). Root pruning results in water stress and likewise reduced photosynthesis (Richardson and Row, 1977a; 1977b). Net assimilation in apples recovers beyond pre-treatment levels three to seven weeks after root pruning (Maggs, 1964). Increases in assimilation occur in response to greater assimilate demand of newly initiated roots (Kramer and Kozlowski, 1979).

Conversely, reduction in root area may also result in increased leaf nutrient concentrations. Root pruned peach seedlings exhibited higher leaf N, P, K, Mg, and Ca concentrations in leaves compared with controls (Richards and Row, 1977). Increased concentrations of nutrients in the plant have been found to occur due to the increased efficiency with which newly initiated root apices obtain minerals from the soil (Atkinson, 1980).

Root pruning in apple may result in increased floral initiation (Ferree, 1976). Reductions in fruit size, fruit yields and pre-harvest fruit drop also result from root pruning (Tukey, 1964; Ferree, 1976). However fruit produced following root pruning treatments contained greater soluble solids concentrations indicating increased quality compared with untreated controls.

### 4.6.8 *Shoot pruning*

Shoot pruning in apple and plum has been found to result in: reduced new root growth and root regeneration (Head, 1967; Atkinson, 1980); reduced net photosynthesis, transpiration and root dry weight (Taylor and Ferree, 1981; 1984); and the temporary diversion of carbohydrate reserves and current assimilates to the canopy at the expense of roots (Kozlowski and Pallardy, 1997).

While both canopy and root pruning have the potential to influence deciduous crop yield, few studies examine the influence of both root and canopy pruning on evergreen tree crop yield or fruit quality. Researchers have, however, conducted studies of canopy pruning and cropping in a number of horticultural crops. We examine several of these cases in: macadamia; citrus; lychee; avocado; and mango.

### 4.6.9 *Macadamia canopy pruning*

In Hawaii, trees of variety 246 in a 9.1 m x 9.1 m spacing were pruned in years 13 and 15 (Warner and Gitlin 1974). Pruning was done by hand in January at 1.5m from either side of the trunk. In the years of pruning (13 & 15) yield was reduced by 30%. In the years following pruning (14 & 16) yields were 18.6% and 8.9% less than the control respectively, although these differences were not statistically different.

Pruning resulted in significant stimulation of vegetative growth. Numerous shoots developed after pruning, especially where larger limbs had been cut, with longer shoots produced by pruned trees compared to controls. On pruned trees, 140 shoots averaged a length of 104cm compared to 64.4cm on unpruned trees. Despite the vigorous regrowth, more fruit developed in the centre of pruned trees suggesting that pruning had improved light penetration. Unfortunately there were no details in the paper on how much foliage was actually removed so it was not possible to gauge the severity of the treatments. Liang and Myers (1978) reported that pruning caused a reduction in yield proportional to the amount of wood removed.

Topping of trees was trialled in Australia in 1988 in a high density planting (5 x 3m) of varieties 246 and 508 at Whian Whian in northern NSW (Trochoulias, 1994). Trees were 8.5m before topping and alternate rows were topped at 5.5m. Yields in the topped rows were reduced by 50% and 65% respectively for 246 and 508 variety compared to 1987 yields, whereas yields from the untopped row increased by 63% and 26% respectively for 246 and 508. In 1989, two years after topping, dense overgrowth in the topped rows reduced yield by 80 to 90%. A substantial proportion (38%) of the canopy was removed in this trial which resulted in the extreme response. It may be possible that less severe topping could be used to effectively maintain tree height without significantly affecting yield.

Liang and Chan (1977) used a model to determine the optimal orchard design for light interception in macadamia but the model and some of its assumptions have not been tested in the field. Attempts were made in two undergraduate theses to look at the effect of tree spacing (Broomhall 1987) and pruning (Heselwood 1984) on light penetration and productivity of macadamia orchards. No effect of pruning treatment on canopy light levels was detected. Relationships between light penetration in the canopy, Nut-In-Shell (NIS) yield, kernel recovery and kernel weight were recorded as significant but there was actually either very little change in the parameters over the range of light intensities measured or the responses appeared random. These results probably reflect the difficulties encountered in measuring canopy light levels (DeJong and Doyle, 1985).

In the tree spacing work, Broomhall (1987) found that less light penetrated to lower levels in closed canopies than in open canopies and that this was also associated with proportionally fewer branches producing nuts in the closed canopies. However, the relationship between canopy light level and overall productivity of the orchard was not investigated. Although these studies provide valuable information on physiological response to shading they do not provide an index that can be used to relate canopy structure to orchard productivity.

### **4.6.10** *Timing of pruning in macadamia*

Trochoulias and Burnside (1987a) argued that winter was the best time to carry out pruning because there is very little vegetative growth at that time. They hypothesised that if pruning was done in winter storage carbohydrate would be diverted to reproductive growth in spring instead of vegetative growth.

They claimed that in a pruning trial in a 5 x 3m spacing of H2, 246 and 508 cultivars pruning in October rather than May reduced yields but the results presented do not clearly support this conclusion. Trochoulias and Burnside (1987b) suggested that "annual mechanical pruning in mid-winter appears to reduce competition and increase fruitfulness".

### **4.6.11** *Citrus pruning*

Pruning including sidewall hedging and topping is used routinely in the citrus industry to maintain tree size and alleviate crowding (Rabe 1993; Bevington 1980; Phillips 1978). Pruning in citrus creates the same problems that are often cited in the macadamia industry. That is, it often results in stimulation of excessive regrowth at the expense of undesirable fruiting wood (Phillips 1978). These practices result in a wall of foliage on the outer canopy, which causes increased shading of the inner canopy (Rabe 1993). New growth is stimulated in proportion to the amount of wood removed, being greatest where the most severe cuts are made (Phillips 1978). One industry reviewer (Rabe 1993) advocates a combination of mechanical and selective pruning, with selected branches removed close to the point of origin.

Another problem with vertical hedging of vigorous citrus trees is that the upper portion grows more vigorously and soon shades the lower portion. Therefore it is considered desirable to hedge at an angle which would delay this effect (Phillips 1978). 'Hamlin' orange trees were hedged at angles of $5^{o}$, $10^{o}$, $15^{o}$ and $20^{o}$ from the vertical. Longer shoot growth occurred with the two greater angles but there were no differences in the average yield after 6 years (Phillips 1972).

Anecdotal evidence from Florida suggests that the more vigorous the trees, and the closer they are planted, dictates earlier and more frequent pruning intervention so that only light cutting is necessary and crop reduction is minimised (Phillips 1978). Further anecdotal evidence from Florida indicates that some growers have at least partially solved the regrowth problem after pruning by controlling nitrogen application. Nitrogen is needed for tree health and fruit production but excessive amounts could result in unwanted vegetative growth (Phillips 1978).

In Australia yield reduction after pruning increases in proportion to the severity of pruning (Bevington 1980), with substantial yield reduction occurring after heavy pruning (Bevington and Bacon 1978). Light pruning results in the loss in production, but is compensated by increased production in the second year (Bevington and Bacon 1978)

Citrus cross-hedging (pruning between adjacent trees in the row) and/or topping was carried out in Florida in a number of orchards with a row spacing of 7.6m and tree spacings ranging from 5.3m to 2.7m (Whitney et al. 1983). Tree age was between 14 and 28 years. In the three years following cross hedging, yields were reduced by 14%. When trees were topped yield reduction increased with the amount removed. Topping at 4.3m yielded 38% less over three years than topping at 5.2m. There was no information on the timing of cross-hedging or topping.

Annual pruning was trialled in Israel in "Clementine" mandarin orchard to improve fruit size and reduce tree size to facilitate harvests (Oren 1988). The trees were planted at 4 x 4.25m and at year 6 they were mechanically topped and hedged at an angle. To prevent a dense growth of the canopy at the pruning line and to permit light penetration into the tree, windows into the canopy were made by removing a major branch from the southern side of the tree. This was done annually at first then every other year. The author claimed that this combination of mechanical and selective pruning resulted in higher yields of large fruit but there was no control to assess the veracity of this.

A pruning and tree removal trial was conducted in a 13-year-old "Tarocco" orange orchard in Italy which had been planted a 6 x 4m (Intriglio et al. 1988). Yield had dropped significantly in year 11 and this had been attributed to overcrowding. Tree height was greater than 7m and the wide overlapping canopies cast shade on the lower and internal parts of the canopy causing leaf fall. Unfortunately, the treatments in this trial were such a combination of different techniques that it was difficult to draw any conclusions about tree response to a specific technique due to a lack of appropriate controls.

The treatment which gave the highest yield represented a combination of 25% of tree removal (1 in 4 trees removed in a diagonal pattern across the row), light side pruning (removal of about 40cm of canopy alongside each row), manual reduction of tree height (about 2m) and "marked manual lighting of inner parts of the canopy" (presumably this meant selective removal of internal branches to increase light availability to the centre of the canopy).

Over three years, this treatment gave a higher yield than a similar treatment which had no topping and only removal of deadwood from the internal part of the canopy. There was no difference between this latter treatment and a treatment which comprised drastic mechanical pruning by removal of about 1m of the canopy alongside the row and topping which removed between 2.5 and 3m of the canopy and also marked lighting of the internal part of the canopy. The drastic pruning (spring) was followed by removal of suckers in autumn and the following spring. The spring pruning treatment caused a significant decline in yield immediately following pruning. However over a three-year period the drastic pruning treatment produced greater yields than the controls.

The largest fruit occurred in the most severely topped treatment and this did not appear to be related to crop load, as fruit size was larger than in treatments that had similar yields. The authors attributed the poor fruit size in treatments with no topping to the lack of renewal of the top branches (although similar fruit weight occurred in treatments receiving slight manual topping). The smallest yields and fruit size occurred in the controls. The authors recommended manual lowering of the canopy over mechanical topping because the former is discriminating in the size of branches being removed.

In Australia, three levels of severity of pruning (removal of 1,2 or 3 years' growth) and three prunings (spring, summer and autumn) were carried out in an 18 year old "Valencia" orange orchard, planted at 6.7 x 6.l m (Bevington 1980). An initial growth flush occurred immediately after spring and summer pruned treatments with a subsequent flush in the following spring. Autumn pruned trees, in contrast, exhibited regrowth immediately after pruning in only 47% of the branches with regrowth in the remaining branches being delayed until spring. There was some dieback of pruned branches where regrowth had been delayed.

Stimulation of vegetative growth in the spring and summer pruned trees increased with the severity of pruning. Both the number and length of shoots increased in the first flush after pruning. This effect of pruning severity on total shoot length (shoot number and length) was also carried over to the second and third regrowth flushes after pruning. Length and number of shoots was also greater in the spring and summer pruned trees in the second flush after pruning than it was in the autumn pruned trees.

Flowering was observed on the second flush following pruning in spring and summer pruned branches but not on branches which had been autumn pruned. Despite this, there was no consistent or significant difference in yield due to the timing of pruning. Yields were reduced in proportion to pruning severity but these differences were not significant. Interestingly, an increased percentage of pruned branches set fruit as pruning severity increased but the author did not discuss the possible reasons or implication of this.

It was concluded that light pruning may be carried out at any time of the year without affecting yield but this is not supported by the data as there was no control to assess whether pruning had any effect on yield. Despite the absence of a demonstrated effect on yield due to timing of pruning the author concludes that autumn pruning is unsatisfactory as the delay in flowering on pruned branches "increases the long term adverse effects on yield" but it is not explained.

Few studies have attempted to examine the physiological response to tree pruning. One study which did consider this aspect is that of Eissenstat and Duncan (1992) who found that removal of a third of the canopy (by topping) of "Valencia" orange on "Sweet Orange" rootstock reduced root growth within 1-2 weeks and reduced root mortality. There was a 20% reduction in root length density. Root length density recovered within 9 weeks and at 9-11months after pruning leaf and root biomass had completely recovered to unpruned controls, apparently at the expense of fruit production. It was suggested that severe pruning may result in large fruit being aborted but no measurements of flowering and fruit set were made. Only differences in yield between treatments were measured.

### **4.6.12** *Lychee pruning*

Lychee exhibits irregular flowering and fruiting between successive years (Batten and Lahav, 1994). Determination of whether newly developing shoots will form leaves or flowers depends on the temperature during early bud development (Batten and McConchie, 1995). When early bud growth occurs at temperatures below $20^0$ C flowers are initiated, while leaves developwhen earl bud growth occurs at temperatures above $20^0$ C (Batten and McConchie, 1995, Menzel and Simpson, 1995). The duration of floral inductive conditions is frequently short (Olesen et al., In Press) and may fall between flushes (Olesen, Menzel and McConchie, In Press). By scheduling pruning it has been demonstrated that its possible to encourage bud growth to occur during periods when of florally inductive temperatures are likely. In addition to increasing the regularity of flowering and fruit set in lychee (Olesen, Menzel and McConchie, In Press; Olesen et al., In Press), pruning results in significant enhancements of light penetration into the canopy, and increased fruit set and retention (Olesen, Pers. Comm.)

### **4.6.13** *Avocado canopy pruning*

Various forms of pruning are used in avocado production (Anderson 1987 and Wolstenholme et al. 1986). These include selective limb removal, pollarding and sandwich pruning. With selective limb removal, branches which intermingle with neighbouring trees and limbs from the interior of the canopy are removed to improve light penetration into the centre of the tree (Anderson 1987). Pollarding usually involves cutting back alternate trees to 1.5 to 2m, leaving stubs of three to five branches. These stumps rapidly put out new growth and production normally starts again in 2-3 years (Wolstenholme et al 1986; Anderson 1987). Sandwich pruning is used as a precursor to tree removal. In this the trees to be removed are gradually cut back over a number of seasons until it is no longer economic to retain the tree. The aim of this method is to avoid a sudden drop in yield immediately following tree removal. Although pruning in avocado is apparently a widespread practice there are few if any documented accounts of the impact of any particular technique on light penetration and yield.

#### **4.6.14** *Mango canopy pruning*

In 45 year old trees in India, the removal of inner branches and a reduction of shoot number in terminal whorls improved yield and fruit colour (Rao and Shanmugavelu 1976). Iyer and Subramaniam (1976) minimised tree size increase by pruning the previous seasons growth to 5cm stumps. However not all varieties responded favourably with flower production and fruit set. Schaffer and Gaye (1989) in Florida removed a quarter of the interior canopy of seven year old mango trees during march 1988. Light penetration improved significantly but there were no differences in fruit colour in the first year. The experiment did not run long enough to measure any affect on yield.

In Queensland shaping and training of mango trees at the early stage of growth is done to give a vase shaped tree with 3-4 leaders. This is done to create an open tree with good light and spray penetration (Whiley 1986). Some orchards use mechanical pruning. In these orchards a side section of a tree is cut back immediately after harvesting. Only part of the tree is done each year. The overall effect is the maintenance of tree height and the accessing of light (Whiley 1986).

### 4.7 Tree removal

The amount of light transmitted to the orchard floor increases as the intensity of tree thinning increases (Palmer and Jackson, 1972; Palmer, 1989). Computer simulations demonstrate that 21% greater seasonal photosynthesis could occur in thinned versus unthinned lodgepole pine stands (Donner and Running, 1986). Similar modelling or experiments relating physiological responses to improved light penetration and yields of tree crops have yet to be performed. We detail tree thinning studies in macadamia, citrus and avocado below, citing yield figures where they are available.

### 4.7.1 *Macadamia tree removal*

In Hawaii (Hamilton et al. 1978) 16 year old trees of cultivar 246 and 508, planted at 7.3m x 7.3 m, were removed within the row on the diagonal to create a spacing of 10.4m x 10.4m. Trees were removed in the Spring. There was a significant yield increase per tree in the years following removal. Yield per ha in the year immediately following thinning were reduced by 11% and 30% for 246 and 508 respectively. There was no differences in the yield per hectare before and after tree removal. Although for variety 246 for the 8 years after tree removal yield was on average 2t $ha^{-1}$ greater than before tree removal. There were no control trees so the differences could also be due to seasonal differences.

In Australia, in a high density (5 x 3m) orchard every second row was removed to leave a spacing of 10 x 3m (Trochoulias 1994). A 20% increase in yield per tree occurred in the year following tree removal and 80 - 100% increase was recorded two years after thinning. There was no detail of tree age at time of removal or any description of the stage of crowding (eg. tree size).

### 4.7.2 *Citrus tree removal*

Response to tree removal in citrus has been variable. In some cases it has resulted in equal or higher yields (Perhson 1974) in others yields have been lower in a long term comparison (Thulberry 1967). Discrepancies may be due to effects of cultivar, differences in tree vigour, local conditions and the stage of crowding.

Two tree removal trials were carried out in orchards in Florida (Whitney et al. 1983). In one, every second tree or every 4th tree within the row was removed from a 7.6 x 3m planting when the trees were 14 years old. Trees were removed largely with the aim of improving access for picking and moving around trees and not to improve light availability and yield. In the year following tree removal yield was reduced by approximately 30% where every 2nd tree was removed and by approximately 20% where every 4th tree was removed. In years two and three there was very little difference in yields between treatments. However, this may have been due to a severe freeze which had a considerable effect on yield.

In a second tree removal trial every 5th tree in the row was removed from a 7 x 2.7m planting when the trees were 12 years old. There was very little difference in yields between this treatment and the control. In a 20 year old 'Valencia' orange orchard in Australia trees were removed from within the row from a spacing of 6.0 x 3.3m to create a spacing of 6 x 6.6m (Matthews 1987). Prior to tree removal in January 1984 the orchard was yielding 7.2t/ha. In January 1987 yield had increased to 9.6/ha. Unfortunately, there was no information on yields in 1985 or 1986.

### **4.7.3** *Avocado Tree Removal*

Orchard thinning in avocado is usually practiced by removing trees within the row on the diagonal (Wolstenholme et al. 1986). In an orchard in Maleny in south east Queensland, yield actually increased from 23 tonnes per hectare off 272 trees to 25 tonnes per hectare off 138 trees the next year (Wolstenholme et al. 1986). In a 'Fuerte' orchard in California tree thinning was postponed (based on the start of tree intermingling) for 5 years. Average yield just before crowding (years 10 -14) was 9.8t/ha. During the period the orchard was crowded (years 15-19) average yield dropped to 8.6t/ha, while for the first three years after tree thinning it was 14.1 t/ha (Wolstenholme et al. 1986). In the avocado industry in South Africa, many trees are planted at around 400 trees per ha and later removal of alternate trees is required to avoid overcrowding. A final stand of mature trees is reached after three thinnings which remove up to 88% of the planting (Kohne and Kremer Kohne 1990.)

## 4.8 Conclusion

Deciduous tree crop canopy function and fruit production are determined by the processes of light harvesting by orchard trees, and its conversion to both biomass and fruit production.

It has been demonstrated that floral initiation, fruit set and fruit development all depend on early season assimilate production, derived from the newly initiated deciduous canopy of apple. This result indicates resource partitioning to the development of a seasonal canopy leaves insufficient storage reserves with which to support fruit development processes. Deciduous canopies form quickly, resulting in rapidly forming gradients of illumination through the canopy. Evergreen canopies in contrast, develop over time. Processes of evergreen resource allocation, and the sources of assimilate to supply these functions remain to be determined. Likewise, the optimal light environments for light interception and fruit production in evergreen tree crops are unknown and are likely to differ between crops.

Deciduous tree planting densities represent the primary determinant of crop yields. Tree crop planting densities (>5000 trees ha$^{-1}$) maximise light interception in the early stages of orchard development. Tree pruning and removal are necessary to maintain light interception at levels conducive to high quality, deciduous fruit production. For example, if left untreated, high-density apple, citrus and pear orchards exhibit declining yields several years after being planted due to mutual shading of adjacent trees. Researchers and Orchardists continue to develop pruning and tree removal strategies for optimised light interception, yield and fruit quality of deciduous crops.

Planting densities of evergreen trees by comparison are significantly lower than deciduous tree crops (< 1000 trees ha$^{-1}$ v's > 5000 trees ha$^{-1}$). Significant and sustained yield declines in high-density evergreen orchards have yet to be demonstrated. Several studies into crop responses to evergreen canopy pruning have been conducted covering a range of crops. Compared with the sophistication of deciduous canopy management techniques, pruning evergreen canopies represent rudimentary studies of canopy control. Responses of canopy pruning and tree removal on yield of the orchards needs to be determined. To facilitate these understandings methods to characterise the canopy structure of evergreen canopies need to be developed. These techniques will assist in the determination of how tree pruning or tree removal programs change the structure of trees and light interception of orchards. These factors represent necessary information to assess the efficacy of different canopy management processes.

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## Chapter 5

# The Effect of Orchard Crowding on Yield and the Development of an Orchard Crowding Index.

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## 5.1 Abstract

The move to higher planting in the macadamia industry has resulted in orchard crowding at maturity and, it has been believed, yield decline. Consequently there is a need for information on the effect of overcrowding on yield.

In this chapter we report on investigations into the relationship between yield per ha and several indices of orchard crowding. These included; percentage ground covered by the canopy, canopy volume per ha, and orchard light interception.

Twenty-one monitoring sites were established in cultivar 344 orchards selected to represent a range in stage of crowding. Fifteen sites were in NSW and six were in Queensland. Yield and quality data and tree dimensions, were collected at each site for four and three years in NSW and Queensland respectively. Light interception in a selection of NSW sites was measured in 1996.

The results indicated that yield decline could occur at a much later stage than expected. Maximum yields tended to occur in orchards with high ground cover. Yield decline was observed at the most crowded site but data from only one site cannot be considered as conclusive evidence of yield decline due to crowding.

Of the different canopy indices assessed percentage ground cover appeared to be the last predictor of yield. It was comparable to light interception but light interception is more difficult to measure. Unfortunately percentage groundcover lacks precision at the crowded end of the range. More work is required to characterise orchard crowding if we are to successfully predict yield decline.

Continued monitoring of sites is required to confirm if and when yield decline occurs. Extended monitoring is required because of substantial year to year variation in yield in macadamia as well as the loss of several key sites at the end of the fourth season.

## 5.2 Introduction

A move to high density planting in the Australian macadamia industry in the late 1970's and early 1980's has resulted in earlier crowding in orchards. In the early 1970's the most common row and tree spacing was 10m x 5m (200 trees per ha). In order to increase production in the early life of the orchard, spacings were reduced to, most commonly, 8m x 4m and 7m x 4m (312 and 357 trees per ha) and in some instances orchards were planted as closely as 5m x 3m (666 trees per ha). Crowding of trees both along the row and across the row in these plantings is more severe than in the wider spacings and occurs earlier in the life of the orchard. Orchard crowding potentially can reduce yield and quality through shading; hinder machinery access and spray application; create a higher disease risk and reduce the vegetation cover on the orchard floor which leaves the soil more vulnerable to erosion.

One of the difficulties facing a grower in managing an orchard which is becoming crowded is determining when yield is affected. As the orchard becomes crowded the productive zone of the canopy moves up through the tree. This makes it very difficult to judge the overall productivity of the tree and orchard from a visual assessment from the ground. Even if a grower does keep accurate yield records for individual blocks within the orchard, large seasonal variations in yield make it difficult to distinguish a seasonal effect from a genuine downward trend in yield. There have been a number of reports of dramatic drops in yield in crowded orchards which have been attributed to overcrowding and excessive shading (Trouchoulias 1994, James 1994). However in these reports there were no detailed descriptions of the stage of crowding which could be related to other orchards and perhaps help predict yield decline.

To predict the effect of orchard crowding on yield we need to define the relationship between yield and a direct or indirect measure of orchard light environment. For example, in apple, the relationships between yield and quality and orchard light interception have been used to optimise orchard design.

Palmer and Jackson (1974) found that production in young high density apple orchards increased with increasing light interception between 20 and 60%. Verheij and Verwer (1973) measured light interception by apple orchard canopies in a spacing trial and found that the best crops were produced at 70% interception of incident light. At 80% interception there was a sharp decline in yield which the authors assumed was because this level of interception was incompatible with satisfactory light distribution. This is in agreement with work by Wertheim et al. (1986) who showed that accumulated production was quadratically related to light interception with maximum yield at 75-80% light interception. In most other fruit and nut tree crops, including macadamia, the relationship between light interception and yield have not been studied systematically as it has been in apple.

In a mature orchard, light interception is a function of tree spacing, tree height: to clear alley width ratio and tree shape and leaf area index within the canopy. According to Palmer and Jackson (1977) leaf area index is the largest single factor determining light interception in discontinuous canopies. The relationship between yield and leaf area index has been studied in mandarin (Tachibana and Nakai 1989) and apple (Barnett 1989) but there have been relatively few studies of orchard leaf area index compared to studies on orchard light interception probably because of the laborious methodology involved in directly estimating orchard leaf area index.

Numerous computer models (Palmer et al. 1987; Charles-Edwards and Thorpe 1976; Jackson and Palmer; 1981, 1980, 1979; Palmer 1980, 1977; Palmer and Jackson 1977 and Cain 1972) have been developed in investigate effects of canopy dimensions, spacing and leaf area index on light interception, again particularly in apple. There is a high level of agreement between some of these models and field observations but the work has not yet been extended to many other horticultural crops.

In this study we investigated the relationship between yield and several indices of orchard light environment including: canopy dimensions; light interception and leaf area index to determine which index was the best predictor of yield and yield decline in macadamia. In addition we also investigated the relationship between leaf nutrient concentration and orchard shading.

In some other tree crops specific leaf weight and the concentration of nutrients per unit of leaf area are indicative of the light microenvironment of these leaves and their photosynthetic capacity (Southwich et al. 1990: De Jong et al. 1989). We hoped that this relationship, if it also existed in macadamia could be developed as a crowding index.

In this chapter we report on the investigations into the relationship between yield and canopy dimensions and light interception. The investigations into leaf area index and leaf characteristics are reported in chapters 7 and 8 respectively.

## 5.3 Materials and Methods

*Measurement Sites*

The investigations into the relationship between orchard crowding indices and yield were carried out in 21 sites in commercial orchards (15 in NSW and 6 in Queensland). The sites were selected to provide a range of stages of orchard crowding and were all located in plantings of cv. 344. Each site comprised 6 plots of 3 trees randomly allocated throughout the planting.

*Measurements*

<u>Yield and Quality</u>

Total yield (nut-in-shell), percent kernel recovery and grade 1 kernel were recorded at each of the NSW sites for four seasons (1995, 1996, 1997 and 1998)and at each of the Queensland sites for three seasons (1996, 1997 and

1998). Nuts were harvested at approximately 4-6 weekly intervals between March and September. The number of harvests for each season varied from four to six.

Nuts were dehusked and passed over parallel bars spaced 18 mm apart. Yields reported in this paper are based on nuts greater than 18 mm. A sample of at least 350 g was taken from each plot and dried to determine nut-in-shell (NIS) moisture content which was then used to adjust NIS weights to10% moisture contact which is the industry standard for reporting yields. A sample of 100 nuts were collected from each plot, dried to 1.5% moisture content, cracked to determine moisture content and then floated in tap water to assess the percentage of grade 1 kernel. Standard industry procedures for drying of nut and assessing kernel recovering and grade 1 kernel were followed (Anon. 1995). In 1995 and 1996 the 100 nut sample was collected from the second harvest. In 1997 and 1998 the sample was collected at each harvest.

Canopy dimensions

Canopy dimension of tree height and canopy width were measured in late Spring to early summer between the spring and autumn growth flushes, using fibreglass forestry poles. Canopy width and row and tree spacings were used to estimate the canopy indices, percentage groundcover and alley width. Percentage ground cover is the horizontal cross sectional area of the tree, canopy expressed as a percentage of the planting square. Canopy volume was calculated from the height of the canopy ($z$) and the width ($x$) of the canopy across the row. It was assumed the within row canopy radius ($y$) was half the planting distance and the shape of macadamia canopies to be that of an ellipsoid (Charles-Edwards *et al.* 1986). The volume of the canopy was calculated as half the volume of an irregular ellipsoid as described in equation 5.1.

(Equation 5.1)

$$V = \frac{\pi * x * y * z}{6}$$

Canopy volumes per hectare were estimated by multiplying the mean canopy volume of trees in each replicate by the number of trees per hectare

Light Interception

Light interception was measured in 1996 at eight of the fifteen NSW sites. Measurements of photosynthetically active radiation (PAR) were made below the canopy in 3 of the 6 plots at each site using a Decagon Ceptometer (Decagon Devices Inc. Pullman, WA, USA). The Ceptometer has 80 light sensors placed at one centimetre intervals along a probe. Instantaneous measurements of PAR were made at approximately 60 cm above the ground at 18 locations in the interrow area on each side of the three tree plot, resulting in a total of 36 measurements per plot. Measurements were taken on a two dimensional grid running along the row and into the centre of the row. Readings were taken opposite each of the three trees in the plot and at three points midway between two trees. At each of these six locations within a plot, a reading was taken with the Ceptometer at right angles and adjacent to the tree row and at two more points moving into the middle of the interrow area at ¼ of the row spacing and at ½ the row spacing. A complete set of measurements was carried out at 1000, noon and 1400 EST. A Li-Cor quantum sensor was placed in a nearby unshaded area and PAR readings were logged at one minute intervals. Measurements were made on bright relatively cloud-free days. Output from the Ceptometer had previously been calibrated against the Li-Cor sensor in full sun. The readings from both instruments were integrated over time and the Ceptometer readings under the canopy were expressed as a percentage of the Li-Cor sensor readings in the open, and light interception calculated by subtracting this value from 100%.

Botrytis Infection
Commencing in 1996 sites were assessed for incidence of botrytis infection during flowering. If substantial infection was found, the infection scores were used in the statistical analysis of yield data.

Statistical Analyses
A regression line with percentage ground cover as the x variable was fitted to yield per ha, to kernel recovery and to percent grade 1 kernel, for each year of the project. Widespread botrytis infection was recorded in the 1997 flowering and so a linear model including terms for botrytis infection as well as percentage ground cover was fitted to 1998 yield per ha.

Further analyses were done at the end of the project to determine the effects that other variables had on yield. A six term model was fitted to the data from all years of the project. The fixed terms in the model included: percentage ground cover; tree height; canopy height; canopy volume per ha; tree age and year. In the analysis it was assumed that the sites were equivalent to a random sample from some population, that the three or four years of monitoring constitute a random sample of years and that the trees measured at each site were chosen at random. A further simplification was to assume that the various combinations of years and sites constituted a random sample of environments.

The general strategy was to include some fixed terms in a model and then add linear terms sequentially. At each step, the term added was the one that gave the most significant result from a change of deviance test (Welham and Thompson 1997).

### 5.4 Results

There was a significant linear relationship between percentage ground cover and yield per ha in 1995 and 1996 ($p < .001$), $r^2=0.81$ and 0.54 respectively) (Figs 5.1 and 5.2). Yield increased as ground cover increased even up to 100% ground cover.

In 1997 there was still a significant linear relationship between yield and ground cover but the $r^2$ value was only 0.32. This was partly due to low yields at one of the most crowded sites. (Fig.5.3). The yields were low relative to yields from other sites with similar ground cover and to yield from that same site in previous years. When the data from all years was analysed together it was found that there was a significant decline in yield of –1.6t/ha at that site during the study

In 1998, there was again a significant linear relationship between yield and ground cover but the $r^2$ was only 0.18, even after including a term for botrytis infection in the model. Yield from all sites in this season were much lower than in the previous seasons. Maximum yield was less than 3t/ha.

There was a significant relationship between yield per ha and orchard light interception( $p<.001$, $r^2=.55$) (Fig. 5.4).

The coefficients and standard errors from the multiple term model are shown in table 5.1. A good indication of significance is obtained by dividing the coefficient by its standard error. Of the six terms fitted, percentage ground cover appeared to be the most important determinant of yield per ha. The other important thing to note from this table is that the standard error for year is high indicating substantial variation in yield from year to year.

The analysis also indicated substantial unexplained variation in yield from site to site within years of the order of one t/ha (data not shown).

There was no consistent relationship between either kernel recovery or percent grade 1 kernel and percentage ground cover (Table 5.2). There were significant linear relationships on a few occasions but the correlation coefficients and the slope of the line were both small. In the case of kernel recovery, the slope of the relationship was inconsistent.

## 5.5 Discussion

The most important result from this work is that yield decline due to orchard crowding does not occur as early in the life of the orchard as previously expected. The results from 1995 and 1996 show that the maximum yields tend to occur in orchards with high percentage ground cover. The orchards at this end of the range were 16 year old trees planted at 7 x 4 m. Previously, Trochoulias (1994) and James (1994) had indicated that yield declined due to overcrowding at year 11 in 5 x 3 m and 7x 4 m spacings respectively.

In 1997 there was a drop in yield at the most crowded site. Yield declined relative to previous seasons and relative to yield from sites with similar ground cover. The decline was statistically significant over the four years that yield was monitored However because yield decline occurred at only one site we can not rule out the possibility that some other factor not directly related to orchard crowding is causing yield decline. Consequently this can not be considered as conclusive evidence of yield decline due to overcrowding.

We had anticipated that continued monitoring of the other high ground cover sites in the next two to three seasons would have provided more conclusive evidence one way or the other. However this has been made more difficult for two reasons. Firstly, in 1998 yields at all sites were substantially lower than in previous seasons as were yields in a large proportion of the industry. Botrytis infection may have accounted for some of the yield reduction but yields were low even at sites with very little botrytis. This made it very difficult to show a relationship with ground cover as obviously some other unexplained seasonal effect was having a much greater impact.

The main reason is that we are unlikely to find supportive evidence of yield decline at the other sites in the time frame indicated above is that at the end of the 1998 harvest trees were removed from three sites which had very high ground cover. These sites were our most crowded sites after the one that had declined in 1997. This obviously has left a considerable gap in the range of crowding in the orchards that we are monitoring. The next most crowded sites left in the trial were, at the end of 1998, two to three seasons away from being in a similar stage of crowding. :This has set back the opportunity to confirm yield decline by two to three seasons.

As sites increased in ground cover over time it became more difficult to identify differences in crowding using percentage ground cover, particularly at the crowded end of the range. This was because percentage ground cover for the more crowded sites tended to merge at the high end of the range as they approached 100% ground cover. Obviously, once an orchard reaches full canopy closure it is not possible to measure any increase in crowding/shading using percentage ground cover. Consequently, in the later years of the project, some sites had similar ground covers despite visible differences in volume of productive canopy and amount of dead wood within the canopy.

Further analyses using other tree based parameters were carried out to determine if they could provide greater resolution of measurement of crowding. These parameters included tree height and canopy volume per ha. However results from these analyses showed that over all the years of the study, percentage ground cover was better than these parameters as a predictor of yield. It was surprising that canopy volume accounted for so little of the variation in yield. We had expected that because the volume calculation integrates percentage ground cover and tree height it would provide a better index of crowding than ground cover alone. It is also difficult to understand why the coefficient for canopy volume per ha was negative. The limitation of this particular analysis is that there are substantial correlations between variables, so it is not always possible to disentangle their effects. It is also possible that the order in which the terms were added to the model affected the outcome. Further examination and analysis of the data will be carried out to try and overcome these problems.

Orchard light interception was comparable to percentage ground cover in predicting yield. However it is much more time consuming to measure and is dependent on sky conditions. We measured light interception by taking spot measurements at noon and two hours either side. It is possible that measurement of total daily light interception may help distinguish between the more crowded sites.

The analysis also showed that there was substantial variation in yield from year to year. This confirms the need for long term monitoring to identify yield decline. It also highlights the difficulty and the danger a grower faces in attempting to distinguish a seasonal effect from a genuine downward trend in yield.

We could not detect any consistent relationship between percentage ground cover and either kernel recovery or percent grade 1 kernel. This was surprising as shading has been reported to cause lower kernel recovery and oil content (Stephenson and Trochoulias 1994). However this occurred on trees in pots which had been completely covered with shadecloth. It is possible that in the orchard situation long distance transport of carbohydrate from well illuminated parts of the canopy can maintain quality in the shaded sections. It is possible that oil content is affected by orchard crowding but results from this study suggest that orchard crowding is unlikely to affect grower returns under current quality assessment procedures. Much more detailed work would be required to determine if orchard crowding is likely to affect other quality attributes such as roasting quality and shelf life.

This work has shown that yield decline due to crowding does not occur as early as expected. This suggests that canopy management technique aimed at alleviation crowding could be delayed. However, there are other factors associated with crowding which should be considered. These include: a potential increase in soil erosion as orchard floor vegetation declines; delayed access for harvest during wet periods which can result in substantial reduction in nut quality and/or increased labour costs for hand picking; potential increase in disease risk. There may be little point achieving high nut in shell yields in the short term if if these other factors are adversely affecting the economics and sustainability of production.

A number of parameters have been assessed for suitability as an orchard crowding index. As well as the ones reported in this chapter two other parameters have been assessed as part of these project. These are leaf area index and leaf nutrient levels and are reported in chapters 7 & 8 respectively. Of the indices assessed so far percentage ground cover appears to be the best predictor of yield but it lacks the resolution required to distinguish between very crowded sites. Other means of characterising orchard crowding need to be investigated if we are able to successfully predict yield decline. In the short term assessment of alternative techniques has also been delayed by the loss of several of our most crowded sites.

Due to the substantial year to year yield variation in macadamia and the loss of key crowded sites, continued monitoring of the remaining sites for several more seasons is necessary to enable us to conclusively determine if and when yield decline occurs.

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Figure 5.1. Relationship between nut-in-shell per ha in 1995 and the percent of ground covered by the canopy ($p<.001$, $r^2=.83$)

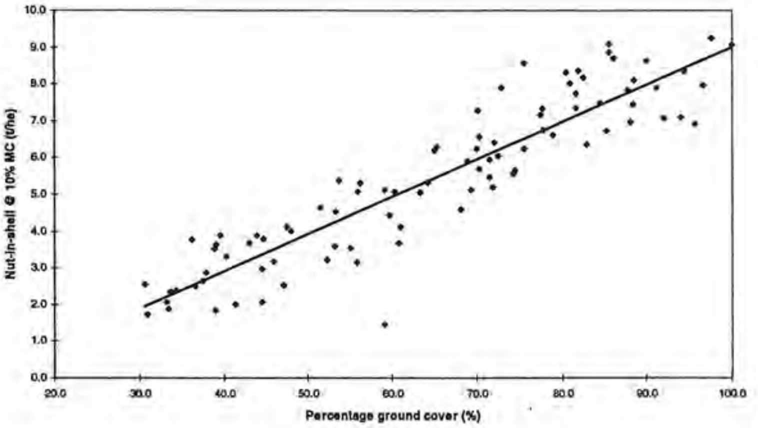
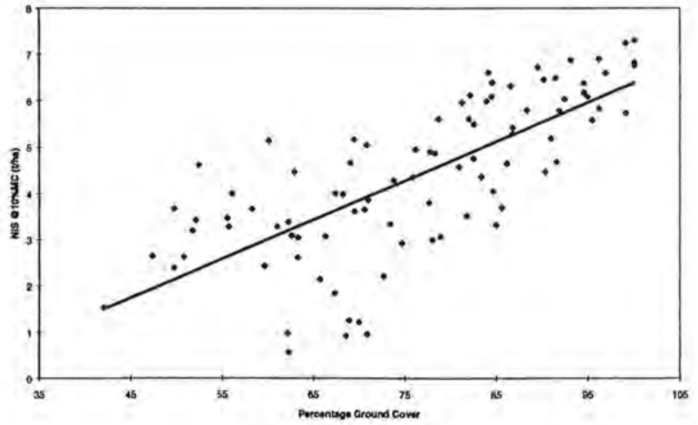


Figure 5.2. Relationship between nut-in-shell per ha in 1996 and the percentage of ground covered by the canopy ($p<.001$, $r^2=.54$)



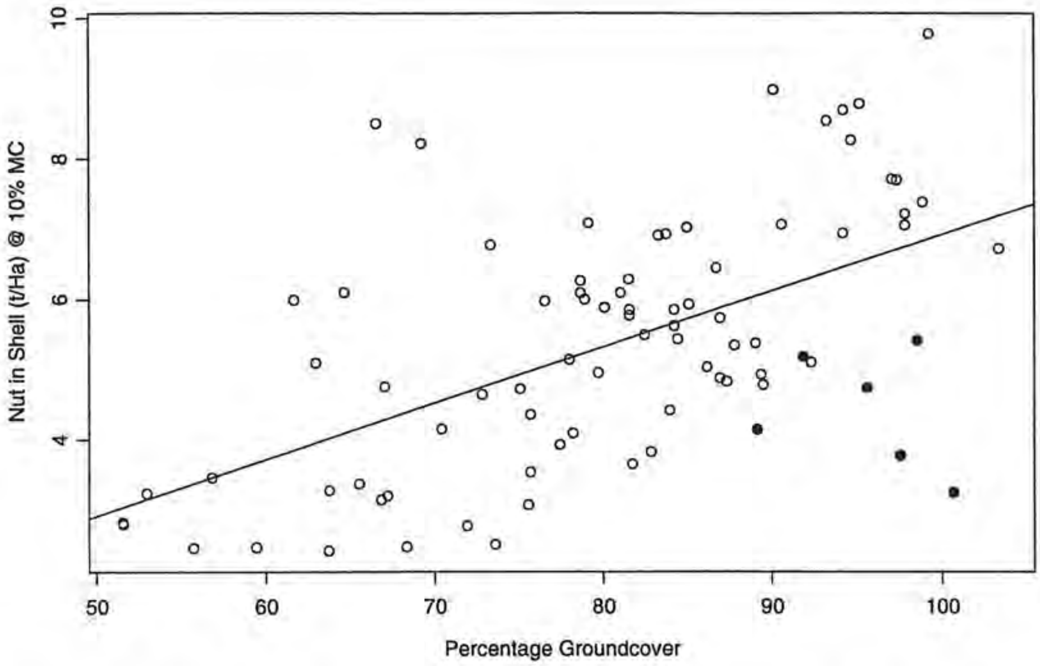


Figure 5.3 Relationship between nut-in-shell per ha in 1997 and the percentage of ground covered by the canopy ($p<.01$, $r^2=.32$) Solid circles are values from the most crowded site

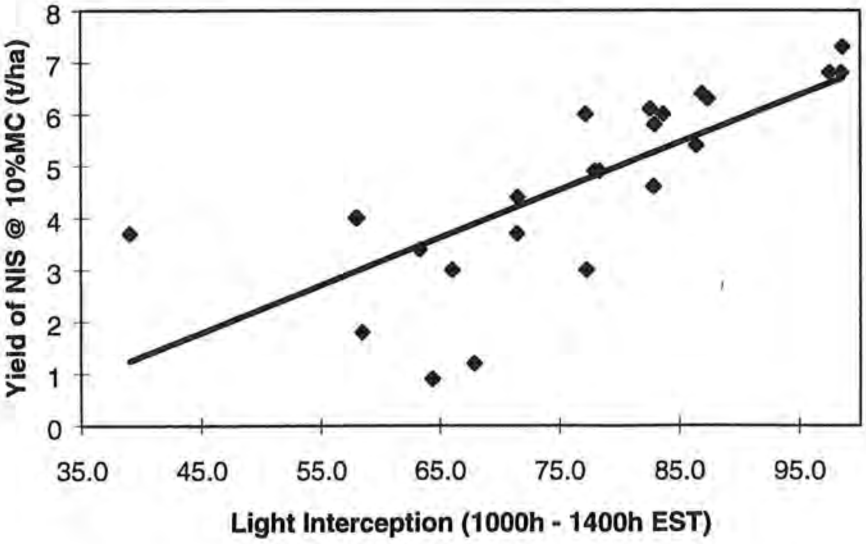


Figure 5.4 Relationship between NIS per ha in 1996 and orchard light interception (1000h - 1400h EST) ($p<.001$, $r^2= .55$).

|  | **p-value** | **R$^2$** |
|---|---|---|
| **1995** |  |  |
| Kernel recovery (harvest 2) | <.01 | .13 |
| Grade 1 (harvest 2) | ns | - |
|  |  |  |
| **1996** |  |  |
| Kernel recovery (harvest 2) | <.01 | .24 |
| Grade 1 (harvest 2) | ns | - |
|  |  |  |
| **1997** |  |  |
| Kernel recovery (harvest 1) | ns | - |
| Kernel recovery (harvest 2) | ns | - |
| Kernel recovery (harvest 3) | ns | - |
|  |  |  |
| Grade 1 (harvest 1) | <.01 | .27 |
| Grade 1 (harvest 2) | .02 | .07 |
| Grade 1 (harvest 3) | ns | - |
|  |  |  |
| **1998** |  |  |
| Kernel recovery (harvest 1) | ns | - |
| Kernel recovery (harvest 2) | .02 | .07 |
| Kernel recovery (harvest 3) | ns | - |
|  |  |  |
| Grade 1 (harvest 1) | .01 | .07 |
| Grade 1 (harvest 2) | ns | - |
| Grade 1 (harvest 3) | .02 | .06 |

Table 5.1 Summary of regression models for yield and quality

|  | All data |  | Sites with four years data |  |
|---|---|---|---|---|
| Random *effects* | Site.year | site*year | site.year | site*year- |
| *Fixed effects* |  |  |  |  |
| Ground cover | 0.058±0.008 | 0.061±0.009 | 0.066±0.010 | 0.071±0.010 |
| Tree age | 0.119±0.053 | 0.103±0.060 | 0.151±0.061 | 0.142±0.066 |
| Year | -0.872±0.145 | -0.888±0.299 | -1.040±0.154 | -1.041±0.383 |
| Canopy height | 0.457±0.126 | 0.494±0.128 | 0.213±0.181 | 0.200±0.183 |
| Canopy volume | -0.018±0.007 | -0.020±0.007 | -0.008±0.010 | -0.009±0.010 |
| NSW v Qld | 0.927±0.449 | 1.025±0.502 | - | - |

Table 5.2: Nuts in shell, t/ha, six term model

# Chapter 6

## The Effect of Tree Removal and Hedging on Yield and Quality in Macadamia.

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### 6.1 Abstract

This study compared the yield from replicated blocks of trees that were either lightly mechanically hedged, had every second tree from every second row removed, or left as untreated controls. In the harvests following treatment the yields per ha from the untreated controls and hedging treatments were consistently better than in the removal treatment. The yield in the removal treatment was 17%, 22% and 18% less than the control treatment in successive years. Trees in the removal treatments tended to drop a greater proportion of the crop in the first harvest. These treatments did cause significant changes in nut quality but these changes were not consistent across harvests. In the short term these results would not support the publish reports of yield increases due to tree removal and actually suggest a reduction in crop. This reduction due to tree removal is supported by results from grower trials.

### 6.2 Introduction

Management techniques such as hedging and tree removal have been used in the industry to maintain access and improve light penetration in crowded orchards but there is little information on the effect of these techniques on yield or quality.

In Hawaii, hedging in macadamias reduced yield by 30% in the season immediately following hedging and by 19% and 9% in the next two years (Warner & Gitlin 1974). However there was no information in this study on how much foliage was removed by hedging. In citrus (Bevington 1980), yield reduction increases in proportion to the severity of pruning. Anecdotal reports in the Australian macadamia industry suggest that light hedging can be used to maintain access without reducing yield.

Tree removal in macadamia in Hawaii in cultivars 246 and 508 resulted in an increase in yield per tree of more than 100% relative to the average yield over the seven previous years (Hamilton, Fukunaga & Ito, 1978). There was an average increase of 15% in yield per ha over the 14 years following removal (16th to 24th year) compared to the years prior to removal (10th to 16th year) but this increase was not statistically significant. Unfortunately, because of the lack of statistical significance of the comparison and the absence of a control in the experiment this study does not give a reliable indication of the effect of tree removal on yield in macadamia.

In citrus, the response to tree removal has been variable. In some cases it has resulted in equal or higher yields (Perhson 1974) and in others yields have been lower in a long-term comparison (Thulberry 1967). Discrepancies may be due to effects of cultivar, differences in tree vigour, local conditions and the stage of crowding. Tree removal is not use routinely in the citrus industry as a canopy management technique.

Tree removal is practised in the avocado industry although evidence of a net benefit in yield per ha is based on comparisons of yields before and after tree removal rather than an unthinned control (Wolstenholme, Whiley and Piccone 1986).

The aim of this component of the project was to collect reliable data on the effect of canopy management techniques on yield and quality in macadamia. We did this in three ways. Firstly, we conducted a fully replicated and randomised trial comparing pruning and tree removal. Secondly, we facilitated growers' canopy management trials and collated the results. And thirdly we collected extra yield data at some of the measurement sites described in chapter 5 where different canopy management strategies had been carried out. At some of these sites the grower cooperator carried out tree removal but left our monitoring plots buffered. We set up extra monitoring plots in the treated areas at these sites and paired them with our original plots to assess the effect of the treatment. The results of all the studies from the three areas just described are presented in this chapter.

## 6.3 Part I Hedging and Tree Removal Trial

### 6.3.1 Materials and Methods

*6.3.1a Trial Site and Treatments*

The trial was carried out in a commercial orchard near Alstonville, New South Wales (29°S). The orchard comprised nine year old trees, cultivar 344, planted at 7 m x 3.5 m. Average tree height was 6.5 m and canopy width across the row was 5.2 m leaving an average alley width between rows of 1.8 m. The canopy had met along the row forming a hedgerow. Three treatments: hedging; tree removal; and a control, were first applied to the trees in October 1995 in a randomised complete block design with 6 replicates. Replicates in the hedging treatment and the control each comprised 4 trees while the tree removal treatment comprised12 trees per replicate. This treatment involved removing 25% of the trees by removing every second tree in every second row. The plot in this treatment therefore included 4 trees from the thinned row (TR) and 8 trees from the adjacent unthinned row (UTR). Nuts from each row within the plot were collected separately. To assess the effect of the treatment on a per tree basis yield from each row within the plot was kept separate and the thinned row (TR) and unthinned row (UTR) were treated as separate treatments in the analysis. To assess the effect of treatment on a per hectare basis, yield from the two rows (12 trees) was combined for the analysis.

In the hedged treatment, both sides of the hedgerow were lightly pruned with a mechanical hedger. Between 300-600mm of foliage was removed from each side. Hedging was repeated in October each year of the trial. In the control, trees were left untouched apart from skirting of the canopy for machinery access, which was applied routinely to trees in all the treatments.

#### *6.3.1b Measurements*

Nuts were harvested at approximately 4-6 weekly intervals between March and September for three seasons, 1996, 1997 and 1998. The number of harvests per year varied from two to five. Nuts were de-husked and passed over parallel bars spaced at 18 mm apart. Yields reported in this paper are based on nuts greater than 18 mm. However the de-husked nut-in-shell (NIS) which passed through the bars, and was therefore less than 18 mm, was collected and weighed separately to determine if there was an effect of any of the treatments on the percentage of small nuts produced.

A minimum sample of 350 g was taken from each plot and dried at 105°C to determine NIS moisture content which was then used to adjust the weights of NIS to 10% moisture content which is the industry standard for reporting NIS weight. A sample of 100 nuts was collected from each plot and dried to 1.5% moisture content, cracked to determine kernel recovery and then floated in tap water to assess the percentage of grade 1 kernels. Standard industry procedures for assessing kernel recovery and grade 1 kernel were followed (Anon. 1995). In 1996, the 100 nut sample was collected from each plot at the second harvest. In 1997 and 1998 the sample was taken at every harvest.

#### *6.3.1c Statistical Analysis*

The analysis of the data followed a split plot in time analysis of variance where components of variation are estimated to reflect the stratification of the data into harvests within plots within replicates. Treatment effects were tested for significance against the whole plot strata while harvest effects and the treatment by harvest interactions were tested for significance in the sub-plot strata.

### 6.3.2 Results

#### *6.3.2a Yield*

There was a significant main effect of treatment and year ($p=0.008$, $<.001$ respectively) on yield per ha and no significant interaction between treatment and year (Table 1). Both the control and the hedged treatment consistently outperformed the removal treatment. Yield per ha in the removal treatment was 17%, 22% and 18% less than the control in 1996, 1997 and 1998 respectively. There was no effect of hedging on yield in any year.

| Treatment | Year |  |  | Mean yield |
|---|---|---|---|---|
|  | 1996 | 1997 | 1998 |  |
| Control | 6.16 a | 7.23 a | 3.43 a | 5.61 a |
| Hedged | 6.46 a | 6.83 a | 4.12 a | 5.81 a |
| Removal | 5.13 b | 5.67 b | 2.78 b | 4.52 b |
| Mean yield | 5.92 a | 6.57 b | 3.44 c |  |

Table 6.1. The effect of treatment and year on nut-in-shell (@10% moisture content) per ha. Means followed by a common letter are not significantly different (P = 0.008, <0.001 for treatment and year respectively

There was a significant effect of treatment, year and the interaction on yield per tree. (Table 6.2.) Yield per tree in 1996 and 1997 in the thinned row of the removal treatment (Removal-TR) was greater than the control, the hedged treatment and the unthinned row of the removal treatment (Removal-UTR). Yield per tree in Removal-TR was 26% and 20% greater than the control in 1996 and 1997 respectively. However, in 1998 yield for this treatment was similar to the other treatments.. In 1998 yields of all the treatments were around 50% of those observed in 1996 and 1997. This trend was observed widely in the industry in this season particularly for cv. 344.

| Treatment | Year |  |  | Mean yield |
|---|---|---|---|---|
|  | 1996 | 1997 | 1998 |  |
| Control | 15.10 a | 17.75 a | 8.42 a | 13.76 a |
| Removal UTR | 15.62 a | 16.82 a | 8.52 a | 13.65 a |
| Removal TR | 19.05 b | 21.45 b | 10.28 a | 16.93 b |
| Hedged | 15.83 a | 16.80 a | 10.10 a | 14.24 a |
| Mean yield | 16.40 a | 18.20 b | 9.33 c |  |

Table 6.2. The effect of treatment, year and their interaction on nut-in-shell (@ 10% moisture content) per tree. Means followed by a common letter are not significantly different (P = 0.001, <0.001 and .08 for treatment, year and the interaction respectively).

Trees in Removal-TR also dropped their nuts earlier than trees in the other treatments. On average over the three seasons, the percentage of the total yield which was collected at the first harvest was 57% for Removal-TR compared to 44 %, 45% and 42% for the control, hedged treatment and Removal-UTR respectively (P<0.001).

#### *6.3.2b Quality*

Kernel Recovery: There was no consistent effect of treatment on kernel recovery. In 1996 there was no significant treatment effect. In 1997 and 1998 there were statistically significant differences between treatments in some harvests but the differences were very small (1.1-1.7%) and were not always between the same treatments (Tables 6.3 & 6.4)

| Treatment | Harvest | | | | | Treatment means |
|---|---|---|---|---|---|---|
| | 1 | 2 | 3 | 4 | 5 | |
| Control | 28.3 ae | 30.8 a | 32.2 a | 33.3 ab | 34.1 a | 31.8 a |
| Removal UTR | 29.1 ab | 30.9 a | 32.4 a | 34.1 a | 34.5 a | 32.2 a |
| Removal TR | 29.3 bc | 31.6 a | 32.7 a | 32.9 b | 34.6 a | 32.2 a |
| Hedged | 28.1 dc | 30.9 a | 32.1 a | 33.5 ab | 34.3 a | 31.8 a |
| Harvest means | 28.6 a | 31.1 b | 32.3 c | 33.5 d | 34.4 e | |

Table 6.3. The effect of the interaction between treatment and harvest on kernel recovery (%) in 1997. Means followed by a common letter are not significantly different ($P = 0.099$, $P < 0.001$ for the interaction between treatment and harvest and for the effect of harvest respectively. There was no significant effect of treatment).

| Treatment | Harvest | | Mean yield |
|---|---|---|---|
| | 1 | 2 | |
| Control | 29.2 a | 30.0 b | 29.6 a |
| Removal UTR | 30.4 a | 31.1 a | 30.7 b |
| Removal TR | 28.9 a | 29.4 b | 29.2 ac |
| Hedged | 30.2 a | 30.7 ab | 30.5 ab |
| Mean yield | 29.7 | 30.3 | |

Table 6.4. The effect of treatment and harvest on kernel recovery (%) in 1998. Means followed by a common letter are not significantly different ($P = 0.01$, $< 0.001$ for treatment and harvest respectively.

Grade 1 kernel: As in the case for kernel recovery there was no consistent treatment effect across harvests and seasons. There was no significant treatment effect in 1996. In 1997 and 1998 there significant differences between treatments in some harvests but the differences were not always between the same treatments (Tables 6.5 & 6.6 ) .

| Treatment | Harvest | | | | | Treatment means |
|---|---|---|---|---|---|---|
| | 1 | 2 | 3 | 4 | 5 | |
| Control | 80.1 a | 89.7 ac | 95.4 a | 90.6 a | 89.7 ac | 89.1 a |
| Removal UTR | 81.0 a | 89.2 ac | 93.2 a | 91.8 a | 93.8 a | 89.8 ac |
| Removal TR | 87.8 b | 92.4 a | 97.8 a | 92.2 a | 93.1 ac | 92.1 bc |
| Hedged | 78.0 a | 87.2 bc | 96.4 a | 87.8 a | 88.6 bc | 87.6 ad |
| Harvest means | 87.7 a | 87.6 a | 95.0 b | 90.6 c | 91.3 c | |

Table 6.5. The effect of treatments, harvest and their interaction on grade 1 kernel (%) in 1997. Means followed by a common letter are not significantly different ($P = 0.04$, $<0.001$, $0.03$ for treatment, harvest and the interaction, respectively).

| Treatment | Harvest | | Mean yield |
|---|---|---|---|
| | 1 | 2 | |
| Control | 82.10 a | 77.70 a | 79.90 a |
| Removal UTR | 87.08 b | 84.93 b | 86.01 b |
| Removal TR | 79.77 ac | 81.95 ab | 80.86 a |
| Hedged | 84.03 ab | 82.73 ab | 83.38 ab |
| Mean yield | 83.25 a | 81.83 a | |

Table 6.6. The effect of treatment on grade 1 kernel (%). Means followed by a common letter are not significantly different (P = 0.008 for treatment, there was no significant effect on harvest).

Nut size: There was very small effect of treatment on the percentage of small nuts (ie < 18 mm diameter) and it occurred in only one year, 1998. The percentage of small nuts was slightly greater in the removal treatment (Removal-TR: 6.1%; Removal-UTR: 6.2%) than in the control and hedged treatments (both 4.9%) (p<.02).

### 6.3.3 Discussion

This study has shown that there is a reduction in yield per hectare in the three seasons following tree removal. It has also demonstrated that light hedging does not affect yield in macadamia.

Yield per tree increased substantially immediately following tree removal. This indicates that tree yield had been limited by crowding and the consequent low light. However the increase was not sufficient to compensate for the loss of 25% of the trees from the orchard. The increase in yield per tree in the first season shows that the trees can respond very quickly to improved light conditions which agrees with Hawaiian experience (Hamilton et al. 1978). Tree removal occurred in October, which was too late to affect either flowering or initial fruit set in that season. Therefore the yield increase must have been due to either increased nutlet retention, increased nut size or both. The fact that there was a similar difference in yield between the control and the removal treatment in the second year suggests there had been no extra benefit from improved light conditions during flowering and initial fruit set. This indicates that would have been no advantage in carrying out the tree removal earlier in the season at the start of the trial. This has implications for the timing of other canopy management strategies such as hedging and the selective removal of large limbs from the canopy. We were surprised that yield of trees in the unthinned row in the removal treatment did not increase because half of these trees would have received more light because its neighbour in the adjacent row had been removed.

The earlier nut drop in thinned rows is consistent with previous observations in thinned blocks (Thomson, R. personal communication 1995) and with a study on oil accumulation patterns in nuts from thinned and unthinned blocks of trees (O'Brien and McConchie 1995). The study showed that although final nut oil content was similar for both blocks, nuts from the thinned blocks reached their final oil content earlier than nuts from the unthinned block.

Despite the improved light exposure in trees in the thinned row there was no consistent effect on either kernel recovery or grade 1 kernel. Shading has been reported to reduce kernel recovery and oil content when whole trees have been artificially shaded (Stephenson and Trochoulias 1994 and Liang and Myers 1976)). It may be possible that well lit parts of the canopy can compensate for the more shaded areas by supplying carbohydrate over long distances.

It was no surprise that the hedging treatment did not reduce yield in the first season as only a small amount of wood and foliage was removed. We believed that a light regular hedging regime is more likely to be felt in subsequent seasons as it may not allow sufficient fruiting wood to be retained. Macadamia generally only bears nuts on wood that is at least two years old. Continual removal of wood before it has a chance to reach this stage may affect the cropping potential of the canopy. Because this has not happened over the three seasons it appears that sufficient productive wood is retained behind the hedged surface to carry a crop. A light hedging regime appears to be suitable for maintaining access without either affecting yield or quality. This would be an appropriate strategy in the early stages of crowding but as the trees continue to grow, access could not be maintained without removing increasingly large amounts of foliage and wood with presumably a consequent reduction in production.

The results so far from this trial do not support tree removal as an appropriate strategy for maintaining yield in high-density plantings. In the longer term as the orchard matures and crowding in the control increases the removal treatment may perform better than the control. However any yield decline in the control would have to be very severe to justify the average 20% yield reduction seen in the first three years of this trial and the cost of tree removal and. It is planned to maintain this trial for several more seasons to gain a longer-term understanding of the effect of tree removal and hedging on yield.

## 6.4 Part II - Grower Trials and Comparisons at Treated Measurement Sites

As mentioned in the introduction, we gathered data on tree removal from a number of sources in addition to the main trial just described above. These included growers own trials and comparisons that we made at a number of the monitoring sites described in chapter x where growers had undertaken their own canopy management work. The results from these various comparisons are presented in table 7 together with the results from the main trial. The data includes both within row tree removal and removal of whole rows and covers a number of cultivars and a range in tree ages.

| Tree Removal Treatment | Cv. | Spacing (m) | Tree age at time of removal | Source | Years of data | Yield as a percent of the control | |
|---|---|---|---|---|---|---|---|
| | | | | | | Annual average | 1998 Yield |
| Within row: 25% - every 2nd tree in every 2nd row | 344 | 7x3.5 | 9 | Project | 3 | -19% | -18% |
| Within row: 25% - every 2nd tree in every 2nd row | 344 | 7x4 | 16 | Project | 2 | -18% | -14% |
| Within row: 50% - every 2nd tree in every row | 344 | 7x4 | 11 | Grower | 1 | 12% | -------- |
| Within row: 50% - every 2nd tree in every row | 660 | 7x4 | 11 | Grower | 2 | -26% | --------- |
| Row removal: 50% - every 2nd row | 344 | 6x4 | 9 | Project | 2 | -50% | -47% |
| Row removal: 50% - every 2nd row | 246 | 7x7 | 18 | Grower | 4 | -35% | -27% |
| Row removal: 50% - every 2nd row | H2 | 7x7 | 18 | Grower | 5 | -22% | -4% |

Table 6.7. *The effect of tree removal on yield.* The source of the data is indicated as either "grower" or "project". "Grower indicates the data comes from a trial carried out by a grower. "Project" indicates it is data collected by research staff attached to the project. The first trial in the table is the main trial described in part 6.3 of this chapter.

## 6.5 Discussion

In six out of the seven trials tree removal resulted in an overall reduction in yield. In most cases yield per tree was increased by tree removal but this was not enough to compensate for the loss of trees. These results fall short of expectations, which were largely based on anecdotal reports and the Hawaiian research (Hamilton et al 1978). In citrus variable results following tree removal have been attributed to differences in cultivar, tree vigour, local conditions and stage of crowding (Perhson 1974 and Thulberry 1967). It is possible that in some instances tree removal in macadamias may show a positive results due to variation in these factors. However the data collected in this project, which does cover a number of varieties, tree spacing and ages, suggests the odds are against a positive response to tree removal in macadamia at least in the first three years after tree removal.

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# Chapter 7

## A comparison of direct and indirect estimates of Leaf Area Index of *Macadamia integrifolia* (Maiden and Betcshe)

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### 7.1 Abstract

*Macadamia* (Proteaceae), an Australian evergreen rainforest tree, produces fruit with an edible kernel. This work aims to provide a preliminary means to describe macadamia canopy structure using Leaf Area Index (LAI). Destructive leaf harvests and indirect methods were compared using the Li-Cor LAI-2000 Plant Canopy Analyser (PCA). This device provided estimates of the LAI of individual trees and orchards *Macadamia integrifolia* (Maiden and Betsche).

It was found that in *Macadamia*, LAI is linearly related to light attenuation through the canopy. The PCA generally underestimated the actual LAI, particularly at high LAI values where discrepancies ranged between 30 and 56%. Calibration factors for the instrument were developed to correct for these underestimates. Physical harvests showed macadamia cultivar 344, aged 11 years, exhibited LAI of between 14 and 16. These values represent some of the highest recorded for productive fruit and nut crops.

We determined a calibrated Foliage Area Index (FAI) for three canopy management treatments in macadamia. These treatments included: removal of 25% of trees from the orchard; a minimal pruning treatment in which approximately 30 cm of canopy was removed along rows; and an untreated control. Due to the low resolution of high LAI values, the instrument appears to have limited sensitivity to detect reductions in canopy area following minimal pruning treatments. This suggests an incapacity of the device to detect many phenological processes in macadamia, such as: leaf flushing, or leaf abscission. However, the instrument was sensitive to larger scale canopy manipulation treatments such as tree removal treatments.

## 7.2 Introduction

*Macadamia integrifolia* (Proteaceae) is an evergreen rainforest tree, endemic to southern Queensland and northern New South Wales of Australia (Wrigley and Fagg, 1991). Macadamia produce fruit that have an edible kernel. Extensive macadamia plantings in both Hawaii and Australia, produce kernel on a commercial basis (Wagner-Wright, 1995). Since the early 1980's Australian macadamia orchards have been established at increasingly closer spacings (Cull and Threw, 1987; Trochoulias and Burnside, 1987). Canopies of adjacent trees therefore inter-act at an earlier developmental stage, potentially reducing light availability through the canopy. Assessments of canopy manipulation practices to facilitate optimal light distribution for fruit production require techniques to characterise macadamia canopy productivity.

One such canopy descriptor is Leaf Area Index (LAI). LAI represents the area of leaf above a unit area of ground (LI-Cor, 1991). Numerous devices have been developed to non-destructively estimate LAI (Welles and Cohen, 1996), a far cry from when Watson (1947) coined the term. The LAI-2000 Plant Canopy Analyser (PCA) is such a device, which simultaneously measures diffuse light attenuation through the canopy to estimate LAI (LAI-2000; Li-Cor Inc, Nebraska, USA; Welles and Norman, 1991). However, in many cases, portable LAI measuring devices significantly underestimate LAI values determined using destructive measures (Welles and Cohen, 1996). These instruments therefore require calibration to a particular crop or tree species (Sommer and Lang, 1994).

This paper aims to: calibrate the PCA for the determination of macadamia LAI; and to assess the sensitivity of the PCA to resolve changes in canopy structure following a number of canopy manipulation techniques.

## 7.3 Materials and Methods

### 7.3.1 *Site and tree description.*

The study site was located at Rous Mill, in northern New South Wales ($28^0$ 52' S $153^0$ 24' E). The study orchard comprised monoculture blocks of macadamia cultivar HAES 344 (344), established for 11 years in November 1996 when we performed this work. The trees had been established in a grid pattern at a planting distance of 3.5 m within rows and 7 m apart between rows. We chose four replicate trees that exhibited differences in size and canopy structure from which direct measures of LAI were derived.

### 7.3.2 *Direct estimates of LAI*

Destructive leaf harvests were used to obtain a direct estimate of tree LAI. Each of four harvests represented the removal of approximately 25% of the full canopy foliage from replicate trees. Leaves were placed in plastic bags, transported to the laboratory, stored in a cool room ($4^oC$) until processing occurred within 24h of the leaves being harvested.

Ten sub-samples were taken and weighed from the leaves collected at each harvest. The number and areas of all leaves comprising each sub-sample were measured using a Delta-T leaf area meter (Decagon devices, Pullman, WA, USA). The calibration of the instrument was assessed periodically using a steel plate of known surface area. An estimate of the total leaf area removed from each tree per harvest was calculated by multiplying the mean leaf area per gram of ten sub-samples by the total leaf weight of the harvest.

### 7.3.3 *Direct estimate of individual tree LAI*

Direct estimates of LAI were calculated by dividing the total estimated leaf area from destructive harvests by the projected area of ground covered by the canopy. The area of ground covered by individual canopies was determined before the first harvests. Ground area was determined by measuring the length of a segment between the tree trunk and outer edge of the canopy in $10^0$ increments around the tree. The summation of the area between successive segments represented the total area of ground covered by individual canopies.

### 7.3.4 *Estimation of LAI of individual trees and Foliage Area Index (FAI) of orchards.*

LAI and FAI estimates for individual trees and orchards respectively were derived by correlation between indirect measures of foliage areas resolved using the LAI-2000 Plant Canopy Analyser (PCA) and direct estimates of LAI determined by destructive leaf harvests. In all cases, PCA measurements were made at dawn or dusk when the sun's disk was below the horizon, or under a uniformly overcast sky. The operation of the PCA and techniques used to derive these estimates are set out below.

### 7.3.5 *Indirect estimates of LAI*

#### *LAI-2000 Plant Canopy Analyser (PCA) operation and assumptions.*

Welles and Norman (1991) describe details of the technical and operational procedures for the PCA. In summary, the PCA estimates FAI using simultaneous measurements of diffuse light attenuation through the canopy from five zenith angles, namely: 1-$13^0$; 16-$28^0$; 32-$43^0$; 47-$58^0$; 61-$74^0$. The device comprises a hemispherical lens which projects diffuse radiation received from each of these angles onto five concentric silicon diode detection rings. Restriction view-caps provided with the instrument limit the field of view of the sensor to $270^0$, $180^0$ $90^0$, $45^0$, and $10^0$. These view-caps: limit the field of view in small plots; minimise the effects of canopy gaps or inter-row effects; and mask the operator. A control box logs readings, which are subsequently downloaded to a personal computer for processing using software provided with the instrument. In order for the PCA to estimate FAI, there are several theoretical assumptions made, which include: non-reflectivity of leaf elements to wavelengths less than 480nm; that leaf size is small compared to the field of view of each ring; that the distribution of leaves through the volume of canopy being viewed is random; and that leaves are not oriented in the same direction (Li-Cor, 1991). In practice several of these assumptions are frequently not met (Welles and Norman, 1991; Welles and Cohen, 1996).

### 7.3.6 *Indirect estimates of individual tree LAI derived using the PCA.*

To determine the optimal combination of restriction view cap and the number of detector rings used to make an estimate of macadamia FAI, we used the PCA to measure four trees in each of four blocks randomly located within the study site. A split plot ANOVA was used to examine the effects of the location within the orchard, the number of sensor rings, and the view-cap used on estimates of macadamia FAI. Following these results, the $45^0$ view-cap was attached and PCA measurements were conducted on each replicate tree preceding each destructive leaf harvest. The PCA was used to take eight below canopy readings of individual trees. Each reading was made $45^0$ apart with the sensor located next to the trunk, oriented towards the edge of the canopy. Before and after each series of below canopy readings, a reference reading was taken above the canopy using an elevated platform.

Each measurement with the PCA produced an estimate of Foliage Area Index (FAI) which comprised both LAI and the interference with diffuse radiation penetration through the canopy by non-leaf elements such as branches, limbs and trunks, referred to as the Wood Area Index (WAI). Using the PCA, estimates of WAI were made when all leaves had been removed from replicate trees. Estimates of LAI were determined by subtracting the estimate of the WAI from each estimate of FAI for each tree. LAI estimates were calculated by the successive removal of the contribution of sequential detector rings using the software supplied with the instrument. To assess the contribution of neighboring trees to estimates of LAI, the PCA was positioned 3.5 m from each of two trees with measurements and serial deletions of successive rings performed as described above.

### 7.3.7 *Indirect estimates of orchard FAI*

LAI was measured for four blocks, each comprising nine trees. Each block was centered on a tree subject to leaf removal (see below). Two transects, each comprising 30, evenly spaced, below canopy readings were made on diagonals between rows. At the beginning and completion of each transect, an above canopy reading was made. The $45^0$ restriction view cap was used for all readings and was oriented down and across the rows in subsequent transects. This process was repeated preceding each destructive leaf harvest of the center tree in the block.

### 7.3.8 *Semi-direct estimates of orchard LAI*

Calibrated PCA measurements were used to estimate the LAI of trees adjacent to those from which leaves were harvested. A regression between the total leaf area per removal tree and calibrated LAI was from which the total leaf area of trees surrounding the tree subject to leaf removal were estimated. This value was used to provide an estimate of the total leaf area of the plot bordered by the eight trees and the tree from which leaves were removed. These readings were performed before each destructive leaf harvest. Semi direct estimates of the orchard FAI were derived by dividing the estimated leaf area of all foliage elements visible to the sensor by the area viewed by the sensor using detector rings 1-4, and the $45^0$ view cap.

### 7.3.9 *Relationship between direct and semi-direct estimates of FAI.*

Regression between semi-direct and indirect estimates of orchard FAI was performed using using SigmaStat Version 2.0 (Jandel Scientific, San Rafael, California, USA). Using correction factors derived from this relationship, the FAI of the following canopy manipulation treatments were determined: Control (no manipulation); Hedged (30 cm of canopy removed from both side of trees), and; 25% tree removal (removal of every second tree in every second row).

## 7.4 Results

### 7.4.1 *Estimates of individual tree LAI.*

The influence of the number of detector rings and the type of the restriction view-cap used, and interactions between these factors were analysed using a split plot ANOVA (Table7.1). These results demonstrate significant spatial variability in the Foliage Area Index (FAI) of trees in different parts of the orchard, with small-scale variation between trees in close proximity to each other. These results also demonstrate that the number of detector rings and the restriction view cap used, and interactions between these factors represent significant influences on estimates of FAI. In particular, the interaction between restriction view cap and the contributions of individual detector rings to estimates of FAI warrants attention in order to formulate an appropriate sampling protocol.

Estimates of FAI made using a number of restriction view-caps, the serial deletion of detector rings, and interactions between these factors are displayed in Table 7.2. Using the contributions of rings 1 and 2 and the $10^0$ view-cap resulted in the highest estimates of FAI. While in nearly every case the $90^0$ cap gave the lowest estimate of FAI when combined with any combination of detector rings (Table 7.2). Due to the proximity of neighboring trees within rows, only the contributions of detector rings 1 and 2 to estimates of FAI can be used. LAI estimates of zero were determined when using this sensor configuration, indicating the exclusion of the contributions of canopy elements of trees occurring within the same and neighboring rows.

Lines of best fit between direct and indirect estimates of individual tree LAI were plotted, and are displayed in Figure 7.1 as solid lines. For comparison, dashed lines describing a 1:1 correspondence between these factors are drawn. Linear relationships between direct and indirect estimates of LAI were determined using linear regressions (Figure 7.1, Table 7.3). These regressions demonstrate that light attenuation through the macadamia canopy is linearly related to LAI. The contributions of each sensor ring to estimates of LAI were evaluated by sequential deletion of each ring from LAI estimates using the software supplied with the PCA. Estimates of LAI based on all rings are shown in Figure 7.1a, while figures 7.1b to 7.1e represent estimates of LAI resulting from the serial deletion of the contribution of successive rings to estimates of LAI. In all cases, significant divergence between direct and indirect estimates of LAI and a 1:1 correspondence of these factors was apparent. Divergence between these factors was greatest at high values of directly determined LAI, although this divergence was minimised by reducing the number of rings used to calculate LAI.

A comparison of the mean estimate of directly and indirectly determined values of LAI for individual trees are displayed in Table .4. Also displayed in Table 7.4 is the ratio of Wood Area Index (WAI)/LAI, where estimates of LAI and WAI were calculated using the contributions of detector rings 1-2. Direct estimates of total tree values of LAI varied between 11.85 and 16.25, while corresponding indirect estimates varied between 6.04 and 8.46. The ratio of WAI/LAI exhibited variability in estimates between 0.23 and 0.44. In both cases, trees exhibiting the highest and lowest directly determined estimates of LAI corresponded with the lowest and highest estimates of WAI/LAI, respectively.

Regression equations relating direct and indirect estimates of LAI determined using the $45^0$ restriction view-cap, are displayed in Table 7.3. In each case the standard error of the estimate increased as the number of rings contributing to each LAI estimate decreased. Likewise, estimates of standard errors for both the regression gradient and constant increased with decreasing number of rings incorporated into each estimate. The highest adjusted $r^2$ values occurred when the contributions of rings 1-3, and 1-2 were included in computations.

### 7.4.2 *Semi-direct estimates of orchard LAI*

A regression between the total leaf area per removal tree and calibrated LAI was performed (Total Leaf Area = -20.35 + 18.53*($LAI_{calibrated}$) s.e. of the fit = 1.184, F = 137.74, Adjusted $r^2$ = 0.95) from which the total leaf area of trees surrounding the tree subject to leaf removal were estimated. The relationship between direct and indirect estimates of orchard FAI and semi-direct estimates of LAI is displayed in Figure 7.4. The regression coefficients of this relationship are shown in Table 7.5, from which the correction factor for the PCA's underestimate of FAI is derived. The corrected estimates of orchard FAI following various canopy manipulation treatments are shown in Table 7.6.

## 7.5 Discussion

Light attenuation through *Macadamia integrifolia* canopies is linearly related to Leaf Area Index (LAI). However, the LAI-2000 Plant Canopy Analyser (PCA) increasingly underestimates LAI as directly determined LAI increases. We developed a correction factor for this underestimate, so that PCA derived estimates of LAI correspond to directly determined values. While the PCA resolved large-scale canopy removal from the orchard, it was unable to resolve changes in leaf area associated with the minimal pruning strategies employed.

Individual tree LAI and orchard FAI values are linearly related to light attenuation through the canopy, although the PCA increasingly underestimated directly determined values as LAI increased. Underestimates ranged between 30 and 56% of directly determined values. Such divergence may result a number of factors including: the departure of macadamia leaf elements from a theoretically assumed random orientation and distribution used for log linear averaging; or the insensitivity of the instrument to resolve low levels of diffuse light penetration through multiple layers of macadamia canopy elements. Detector insensitivity is likely to account for underestimates, as correspondence between direct and PCA estimates of LAI increased as LAI decreased following successive leaf harvests. Similar underestimates at high LAI values are reported in *Pinus contorta* and *P. taeda,* while the PCA overestimated low values of actual LAI (Sampson and Allen, 1995). In contrast, several workers report good agreement between direct and indirect values of LAI (Lang and Xiang, 1986; Sommer and Lang, 1994). These results occur in crops characterised by LAI values below 5, compared to a mean LAI value of 14.6 for individual macadamia trees. In combination these works indicate the PCA exhibits increasing insensitivity as canopy LAI increases.

### 7.5.1 *Orchard FAI*

A two azimuth protocol (involving down and across views performed on successive diagonal transects between rows) has shown good agreement between direct and indirect estimates of orchard FAI in a number of row crops (Welles and Norman, 1991; Hicks and Lascano, 1995). While single azimuth protocols give unsatisfactory relationships (Grantz *et al.*, 1993; Welles and Cohen, 1996). Underestimates of macadamia orchard FAI occurred at similar levels to estimates of LAI for individual trees using the PCA. Underestimates occurred irrespective of the number of down and across row views performed on successive transects using the $45^0$ view-cap. Underestimates may be due to linear averaging of sky and canopy elements from different detector rings into the same below canopy reading. Results from previous studies (unpublished data) suggest that further restriction of the instruments' field of view, using the $10^0$ view-cap to reduce the combination of both sky and canopy in a single below canopy reading did not significantly decrease FAI underestimates. Nor did the serial deletion of the contributions of the various detector rings to LAI, indicating variation due to linear averaging of sky and canopy elements in the same reading represented a minor component of underestimates.

### 7.5.2 *Correction factors.*

The PCA derives LAI estimates using simultaneous measures of diffuse light penetration from five sectors of the sky, and transmitting this radiation to a ring of five circular silicon diode detectors. Removing the contributions of lower sensor rings has improved the accuracy of LAI estimates using the PCA (Villabos *et al.*, 1994; Brenner *et al.*, 1995; Dufrene and Breda, 1995). To estimate LAI of individual trees, this study used only the contributions of rings one and two. This excluded influences of adjacent trees with diffuse radiation penetration into the canopy. This protocol resulted in amongst the strongest relationships between direct and indirect LAI estimates in the present study. Exclusion of lower rings, however, is likely to result in unrepresentative estimates of both leaf angles and total diffuse radiation penetration through the canopy using the PCA.

A number of authors have proposed species specific correction factors to account for clumping of foliage elements and non-random location of leaves and branches within the canopy (Gower and Norman, 1991; Fassnacht *et al.*, 1994; Stenberg *et al.*, 1994; Stenberg, 1996). Calibration factors of the later works represent theoretically derived constants. The current work calibrates the PCA using values derived from the relevant regression equation (Table 7.2) and substitutes them into equation (1) to correct for underestimates of indirectly determined values of LAI made using the PCA.

Corrected LAI= ($PCA_{LAI}$ – regression constant)/(regression gradient) (1)

The current work supports the conclusion that the PCA should be calibrated against direct estimates for a particular crop (Sommer and Lang, 1994).

### 7.5.3 *Pruning and tree thinning.*

This work indicates the PCA does not resolve small-scale changes in LAI that occur in dense evergreen canopies, such as those of macadamia. Events beyond the resolution of the PCA may include: seasonal phenological processes such as leaf flushing; leaf abscission; or the effects minimal canopy manipulation or pruning. To detect changes in LAI due to phenological processes or pruning strategies requires a device of greater sensitivity to low levels of diffuse irradiance occurring beneath macadamia's dense, evergreen canopy.

Mean measures of macadamia LAI represent some of the highest reported for tree species, indicating significant potential for high levels of shading of internal canopy elements. The canopy physiology that supports fruit production under conditions warrants further study.

## 7.6 Acknowledgements

We would like to thank Rod Thomson for the use of trees in his orchard. For assistance with field-work we thank Paul Kristiansen, Russell Priddle, and Steven Muldoon. We gratefully acknowledge the support of the Australian Macadamia Society and the Horticultural and Research and Development Corporation.

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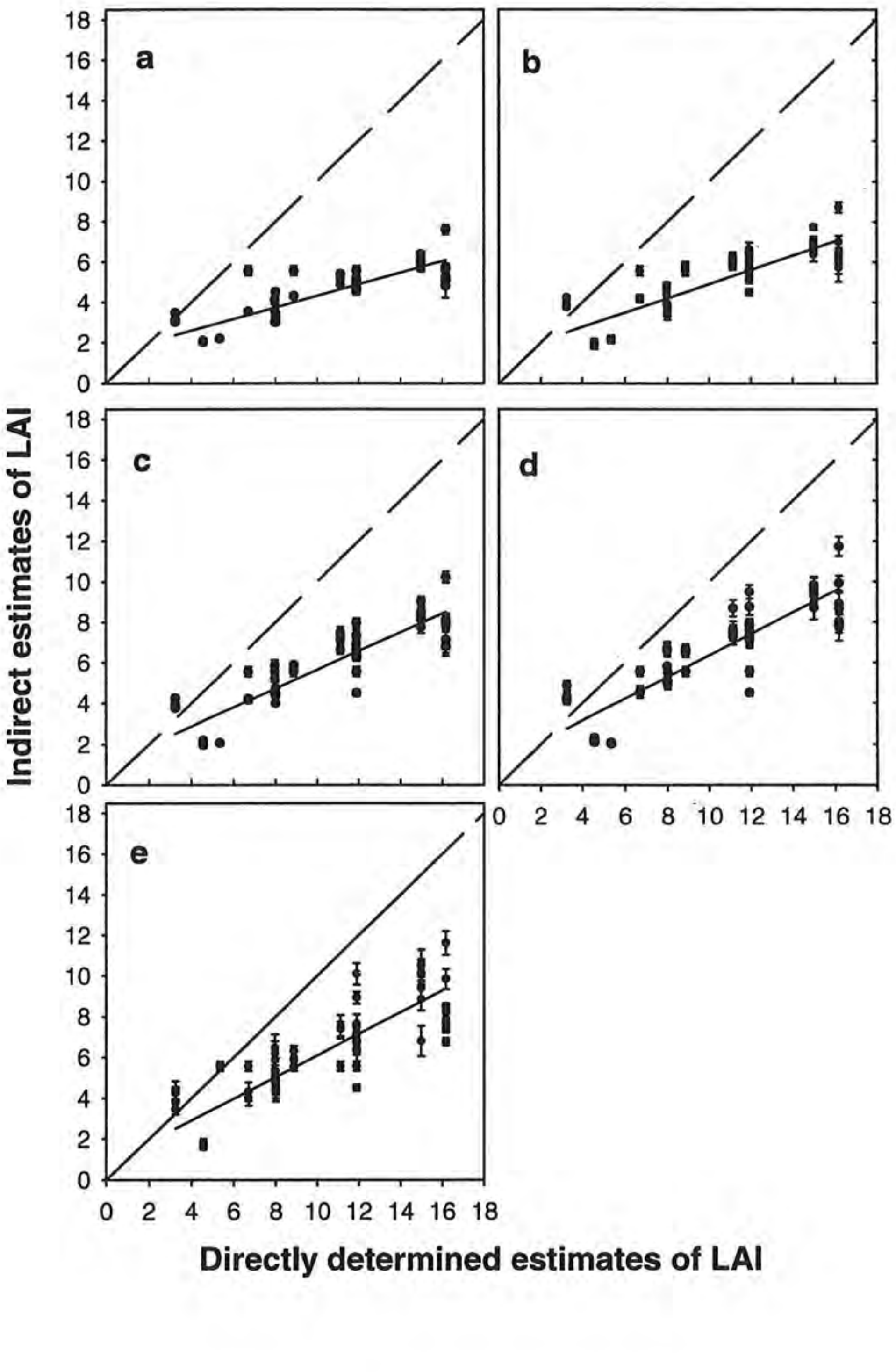
## 7.8 Figures.

**Figure 7.1.** Comparison of direct and indirect estimates of LAI determined using the LAI-2000. • represents the mean ∀s.e. of the estimated LAI determined by the LAI 2000. Estimates of LAI were made by removing consecutive rings' contribution to estimates of LAI, these are shown in graphs: a; which represents the contributions of all rings to estimates of LAI; b = rings 1-4; c rings 1-3; d rings 1-2; and e, ring 1 only. The dashed line represents a 1:1 correspondence between directly and indirectly determined estimates of LAI. The solid line represents the line of best fit between direct and indirect estimates of LAI.

**Figure 7.2.** Comparison of direct estimates of LAI and indirect estimates of Foliage Area Index (FAI) of the orchard determined using the LAI-2000. The dashed line represents a 1:1 correspondence between directly and indirectly determined estimates of LAI. The solid line represents the line of best fit between direct and indirect estimates of LAI.

Figure 7.1


a
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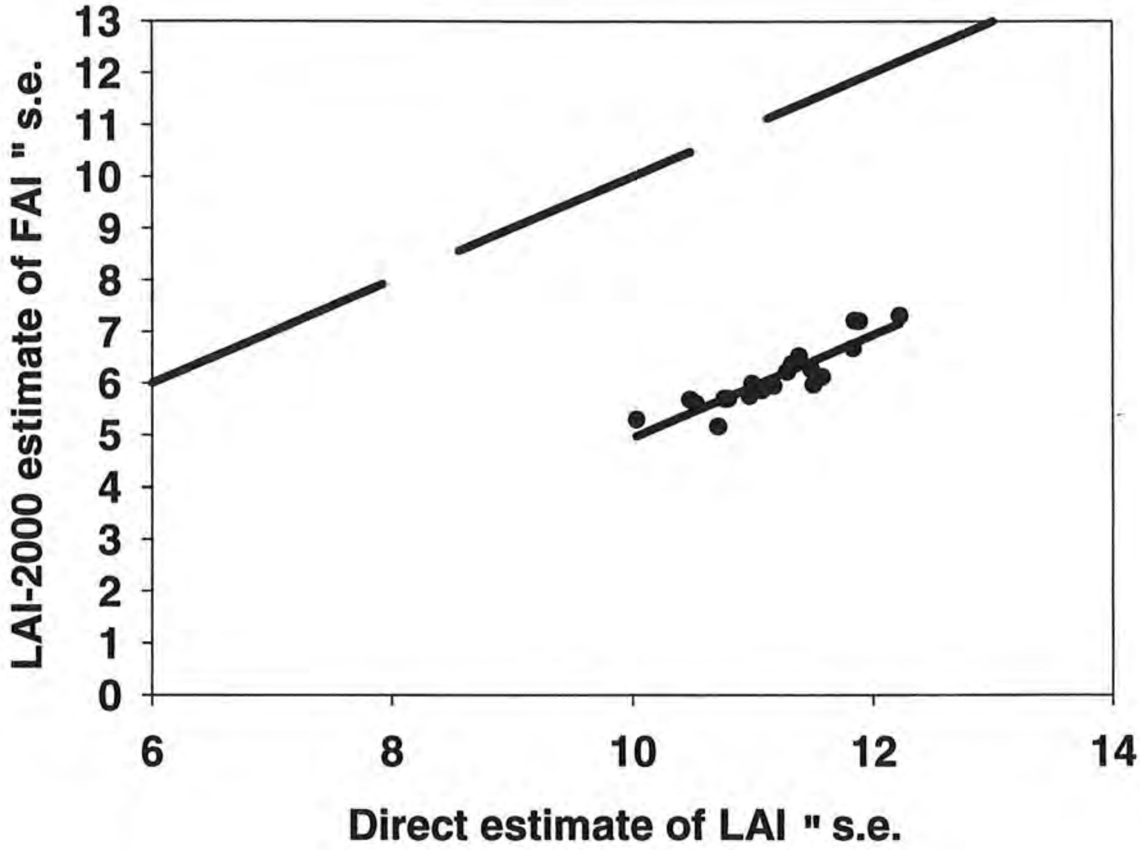
14
16
18
Indirect estimates of LAI
Directly determined estimates of LAI

Figure 7.2


LAI-2000 estimate of FAI " s.e.
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Direct estimate of LAI " s.e.

## 7.9 Tables

**Table 7.1.** Results of a split plot ANOVA examining the effects of sampling block within an orchard, tree (nested within blocks), the number of sensor rings used, the restriction viewcap used and sensor rings (nested within viewcap) on estimates of Macadamia Cv. 344 Leaf Area Index (LAI).

| Source | df | Mean Square | F value | P |
|---|---|---|---|---|
| Block | 3 | 19.62 | 636.19 | 0.0001 |
| Tree*Block | 12 | 0.01 | 0.58 | 0.8531 |
| Ring | 4 | 154.14 | 4997.65 | 0.0001 |
| Cap | 2 | 47.21 | 1530.62 | 0.0001 |
| Ring*cap | 8 | 8.30 | 269.21 | 0.0001 |
| Error | 210 | 0.03 | | |

**Table 7.2.** The results of the progressive removal of the contributions of successive detector rings of the LAI-2000 to estimates of Leaf Area Index (LAI). Means denoted by different letters were found to be different at the $p < 0.05$ level of significance using Tukey's HSD.

| Ring | Restriction View Cap field of view | n | Mean FAI ± s.e. |
|---|---|---|---|
| 1 | 90 | 16 | 7.39 ± 0.13a |
| 1 | 45 | 16 | 9.88 ± 0.12b |
| 1 | 10 | 16 | 11.13 ± 0.16c |
| 2 | 90 | 16 | 8.60 ± 0.12d |
| 2 | 45 | 16 | 9.73 ± 0.15b |
| 2 | 10 | 16 | 10.32 ± 0.13e |
| 3 | 90 | 16 | 6.99 ± 0.12f |
| 3 | 45 | 16 | 8.33 ± 0.13g |
| 3 | 10 | 16 | 8.23 ± 0.14g |
| 4 | 90 | 16 | 6.20 ± 0.14h |
| 4 | 45 | 16 | 6.51 ± 0.14l |
| 4 | 10 | 16 | 6.33 ± 0.15h |
| 5 | 90 | 16 | 5.28 ± 0.12j |
| 5 | 45 | 16 | 5.70 ± 0.14k |
| 5 | 10 | 16 | 5.78 ± 0.13k |

**Table 7.3.** Linear regression tables relating direct and indirect estimates of Leaf Area Index (LAI) as influenced by the serial deletion of the contribution of successive detector rings of the LAI-2000 to estimates of LAI.

| Rings included in estimates of LAI using the LAI –2000 | Regression Gradient ± s.e. | Regression constant ± s.e. | F statistic | Adjusted $r^2$ | s.e. of estimate $S_{y*x}$ |
|---|---|---|---|---|---|
| All rings | 0.288 ± 0.020 | 1.442 ± 0.219 | 202.56* | 0.759 | 0.678 |
| Rings 1-4 | 0.355 ± 0.026 | 1.360 ± 0.287 | 179.92* | 0.737 | 0.887 |
| Rings 1-3 | 0.463 ± 0.028 | 1.018 ± 0.303 | 274.63* | 0.810 | 0.937 |
| Rings 1-2 | 0.525 ± 0.065 | 1.490 ± 0.095 | 243.63* | 0.791 | 1.215 |
| Ring 1 | 1.389 ± 0.105 | 1.535 ± 0.692 | 176.26* | 0.733 | 2.168 |

**Table 7.4.** Direct and indirect estimates of tree LAI and the ratio of Wood Area Index (WAI) to LAI of individual trees.

| Tree | Direct estimate of LAI ± s.e. | Indirect estimate of LAI ± s.e. | WAI/LAI ± s.e. | Ground covered of 344 tree canopy ($m^2$) | WAI/LAI ± s.e. |
|---|---|---|---|---|---|
| 1 | 15.39 ± 0.08 | 7.95 ± 0.13 | 0.243 ± 0.09 | 17.28 | 0.243 ± 0.09 |
| 2 | 14.98 ± 0.06 | 7.82 ± 0.17 | 0.259 ± 0.06 | 17.01 | 0.259 ± 0.06 |
| 3 | 11.91 ± 0.06 | 6.28 ± 0.24 | 0.321 ± 0.14 | 17.28 | 0.321 ± 0.14 |
| 4 | 16.17 ± 0.08 | 8.34 ± 0.12 | 0.246 ± 0.17 | 17.72 | 0.246 ± 0.17 |

**Table 7.5.** Linear regression table relating semi-direct and indirect estimates of Foliage Area Index (FAI) on an orchard basis.

| Regression Gradient ± s.e. | Regression constant ±s.e. | F statistic | Adjusted $r^2$ | s.e. of estimate $S_{y*x}$ |
|---|---|---|---|---|
| 0.996 ±0.113 | -5.014 ± 1.268 | 77.428* | 0.801 | 0.271 |

**Table 7.6.** Calibrated orchard Foliage Area Index (FAI) determined using the LAI-2000. Means denoted by different letters were determined by Tukey's HSD to be significantly different at the $p < 0.05$ level.

| Canopy manipulation treatment | N | FAI ± s.e. |
|---|---|---|
| Control | 6 | $14.34 \pm 0.28^{a}$ |
| Hedged | 6 | $14.26 \pm 0.32^{a}$ |
| Thinned | 6 | $10.04 \pm 0.34^{b}$ |

## Chapter 8

# Leaf nutrient levels in macadamias in response to canopy position and light exposure, their potential as leaf based shading indicators and implications for diagnostic leaf sampling protocols

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## 8.1 Summary

The relationship between leaf nutrient content, leaf age and within canopy light exposure were studied in 10-11 year old *Macadamia integrifolia* cvv. 660, 781 and 344 at Alstonville (latitude 28° 59' S, 149°W) during autumn and spring 1996. Quantum point sensors were placed at 16 positions in the canopy to give a mean 24 hourly photon flux density (PFD) readings which ranged from 13 to 540 $\mu$mol/m$^2$.sec. At each of these positions, the youngest terminal leaf (YTL), the youngest fully expanded leaf (FEL) from a current flush and a 6-7 month old hardened off leaf (HOL) were sampled. In 1997, 12 Alstonville district sites of cv. 344 were leaf sampled (FEL and HOL) at 5 equidistant positions from the bottom, a height of 1.2 m (position 1) to the top (position 5) on the N-NE side of trees in late spring. The sites varied in density from 50-95% ground cover and PFD from the bottom shaded position to the top exposed position in the canopy across all sites increased by a factor of 1.3 to 17.9.

At Alstonville, the leaf parameters N%, P%, specific leaf weight (SLW), N amount per unit leaf area (N area) and P area increased ($P < 0.001$) with increasing PFD. Regression analyses gave maximum $r^2 < 0.59$. Age affected leaf parameters and for N%, N area and SLW; HOL > FEL = YTL and for P% and P area; YTL = FEL > HOL. Cultivar did not affect ($P > 0.05$) N% and N area or SLW while for P% and P area, cv. 660 > 781 > 344.

At the Alstonville district sites, leaf parameters responded to PFD ($P < 0.05$). At each tree sampling position there was a weak negative correlation ($P < 0.05$) between the leaf parameters and percent ground cover which declined with height (PFD). Nitrogen area and P area gave the highest r values and neither were a suitable replacement for percent ground cover as a leaf based shading indicator. Leaf age and site effects ($P < 0.05$) were recorded for all leaf parameters and N% and N area were higher ($P < 0.05$) in HOL than FEL whereas the opposite was recorded for P% and P area.

At position 1, HOL N concentration ranged from 1.3 - 1.8% and P concentration from 0.06 - 0.11% across all sites. At each of the 5 tree positions, at best, the N parameters were very poorly correlated with kernel

yield and for the HOL P parameters, there was a weak negative correlation ($r = -0.521$ to $-0.673$, $P<0.05$) at tree positions 1 and 2 with kernel yield.

Current recommendations to reduce macadamia leaf N concentrations because of detrimental effects of high leaf N on yield were not supported by the current study. We also recommend reducing the current diagnostic adequate P range to 0.06%. Modification of the current diagnostic leaf sampling protocol is recommended to avoid the reduction in leaf N and P concentrations through shading and the cultivar effects on P concentration.

We conclude that the current diagnostic leaf N and P standards cannot reliably diagnose the nutritional status of macadamia orchards.

## 8.2 Introduction

The productivity of trees is dependent on the acquisition and efficient utilisation of light (photosynthetically active radiation measured as photon flux density, PFD). In dense stands of vegetation, light availability decreases with increasing depth in the canopy. In orchards, leaf shading is affected by position on the tree (aspect, height and age), canopy volume and tree density. In dense orchards, it is not so much the gradient in PFD that results in a contrasting light environment but the variation in the amount of time each day that individual leaves are exposed to high PFD (DeJong and Doyle 1985).

The allocation of N throughout the canopy of trees is adjusted to maximise carbon gain (Field 1983). Leaves receiving the most light exposure are thicker and have a higher N content, particularly when expressed on a leaf area basis (N area), and hence photosynthesise at a higher rate (Grindley 1997).

The correlation between PFD and N area has been reported for peach (DeJong *et al.* 1989), several tropical canopy species (Traw and Ackerley 1995; Kitajima *et al.* 1997) and a dicotyledenous herb (Anten *et al.* 1998). Leaf age also affects N area (Traw and Ackerley 1995; Anten *et al.* 1998) and for species with a vertical growth form it has been suggested that leaves receiving the highest light levels contain the highest N concentration because they are the youngest leaves and not as a direct consequence of their immediate light environment.

Preliminary work in macadamia orchards has shown that N area and P area decline down the outside of the canopy as shading increased (S. O'Brien and C. McConchie, unpublished data). This led to the suggestion that leaf based shading indicators could be developed for macadamias to determine the degree of crowding, which exacerbates shading, in macadamia orchards. This would assist with decisions on tree hedging or removal.

This work has implications for macadamia leaf sampling protocols. The recommended protocol is to sample mature 6-7 month old leaves at a height of 1.2 m around a tree (Stephenson *et al.* 1986). This represents leaves exposed to a wide range of light levels which may affect leaf nutrient content.

The current study will determine the feasibility of developing leaf based shading indicators and whether shading of canopies should be considered in a leaf sampling protocol for determining the nutrient status of macadamias.

## 8.3 Materials and methods

This study was conducted in conjunction with a canopy management project where the impact of canopy crowding on macadamia nut production was being studied (McFadyen and McConchie 1996). Percentage ground cover occupied by the canopy was used as an index of crowding. *Macadamia integrifolia* cv. 344 is the most populous cultivar in older commercial orchards and was used in the study.

### 8.3.1 *Alstonville study*

Paired 10-11 year old trees of a number of commercial cultivars of *Macadamia integrifolia* were available in a block of mature trees at the Tropical Fruit Research Station, Alstonville. Only one tree of cv. 344, which has a closed canopy and an upright growth form was available and hence cvv. 660 and 781 were selected to represent closed and open canopies. The aim of this preliminary work was to establish how well nutrient composition and specific leaf weight (SLW) of leaves of different ages would correlate with light availability when precise measurements could be taken. If a good correlation could not be achieved, it would be unlikely that a leaf sampling protocol could be developed to reflect degree of shading and hence degree of crowding in commercial orchards where sampling is more difficult.

Scaffolding was erected around the tree for locating Quantum point sensors (P.P. Systems, Hertshire, UK) at 16 positions (including 2 heights; 2 m and approximately 6 m) around and throughout the tree, representing a wide range of light (photosynthetic photon flux density (PFD)) values. Reference PPS and LiCor (Lincoln, Nebraska, USA) point sensors were located in full sun as references.

Leaf age affects nutrient composition and hence leaves of 3 different ages were sampled. Youngest terminal leaves (YTL) and most recently fully expanded leaves (FEL) were sampled from a recently mature flush as well as hardened off leaves (HOL), about 6-7 months old, from a previous flush. Leaves were sampled from 16 positions representing a wide range of light exposure, from each of 2 trees of cvv. 660 and 781 in 2 seasons and from one tree of cv. 344 in one season. At each of the 16 positions, mean 24 hourly PFD values were determined on a bright, sunny day.

Studies were conducted on the mature summer flush in May 1996 and on the mature winter flush in November 1996.

### 8.3.2 *Alstonville district study*

During October-December 1997 the study was repeated at 12 district sites used in the canopy management project (McFadyen and McConchie 1996).

Tree height varied from 5.8 to 9.1 m between sites. Canopy density varied from 50 to 95%, ground cover (Table 1) and was measured on the northern side of rows running East-West and on the eastern side of rows running North-South from 3 trees in 2 adjacent rows. The maximum and minimum horizontal gap between rows was measured between the adjacent canopies. The area occupied by trees from tree trunk spacings between and within rows was also measured and the horizontal canopy area as a percentage of tree area was calculated.

Leaves were sampled from 5 positions from 1-2 trees from each of 6 replicates. The positions were taken from a vertical transect on the northern (E/W rows) and eastern (N/S rows) corner of each tree where position 1 represented a height of 1.2 m and position 5 was at the top of the canopy. The remaining positions were equally spaced between positions 1 and 5. Young leaves, FEL were sampled from the mature winter flush and old leaves, HOL from the previous summer flush.

**Table 8.1** Alstonville district sites leaf sampled during late spring 1997

| Site | % ground cover |
|---|---|
| Clunes (C) | 50.3 |
| Harriers (H) | 61.8 |
| Pretty Gully (PG) | 62.1 |
| Quandong (Q) | 69.8 |
| Kerrogen 97 (K97) | 72.8 |
| Sara Rous (SR) | 77.8 |
| Fernleigh Park North (FPN) | 80.3 |
| Victoria Park North (VPN) | 80.5 |
| Ainsbury (A) | 81.5 |
| Victoria Park South (VPS) | 82.0 |
| Victoria Park 7 (VP7) | 85.8 |
| Fernleigh Park South (FPS) | 94.8 |

Quantum sensors were erected on a pole at each of the 5 leaf sampling positions on a representative tree at each site to characterise the light environment.

### 8.3.3 *Leaf sampling and chemical analyses*

Leaves were sampled then stored for a maximum period of 2 weeks at 4°C before their area was determined. A planimeter (Paton Electroplan Model EP711) was initially used for leaf area measurements and this was replaced by a video image analysis machine (Delta T image analysis system). In both cases, their calibration was regularly checked from reference material of known area.

Leaves were then immediately dried at 70°C for 4 d in a forced air cabinet for dry weight determination. Leaves were then ground using a cyclone sampling mill to pass a 1 mm sieve and represented a particle size of <0.3 mm. Samples were then stored in air tight containers for chemical analyses.

For the Alstonville study, leaves were analysed for total N, P, K, Ca, Mg, Fe, Zn, Mn, Cu as described previously (Huett and Rose 1988; Huett 1997). For the Alstonville study, leaves were analysed for N and P only.

### 8.3.4 *Statistical analyses*

**8.3.4a** *Alstonville study*

Ninety five regression analyses were conducted between leaf characteristics (SLW = leaf wt per unit area, N area = mg N/cm$^2$ leaf area, P area = mg P/cm$^2$ leaf area and hence for K, Mg, Ca, Mg, Fe, Zn, Mg, Cu) and PFD. The regressions were conducted on the autumn and spring data for the cultivars 781, 660 and 344.

A combined analysis was then conducted on the 1996 data. The aim of this analysis was to identify relationships between leaf nutrient levels and cultivar (344, 660 and 781), leaf age (YTL, HOL, FEL) and light (PFD).

The sampling of the leaves had 3 levels of stratification; the 3 leaf stages were sampled at 16 locations within each tree which were sampled once in 1996 and once in 1997. This lead to use of a "split-plot" study of structure for the variance of the data with years as main plots, trees as sub plots and sites within trees as sub-sub plots.

A split-plot analysis of variance would normally be the appropriate model for analysing these data. However, the cultivar and leaf age main effects were not balanced with respect to the strata of this experiment: cv. 344 was only sampled in spring and all three leaf stages were not sampled at each site. Therefore, mixed models were used for the analysis with random effects designed to reflect the stratification of the data and fixed effects for cultivar leaf age, PFD and all two way interactions.

The full model (ie. with all main effects and interactions) proposed a linear relationship between nutrient level and PFD which is allowed to vary in slope and intercept for each combination of variety and leaf stage. If interactions with PFD are dropped, the model becomes one of parallel linear relationships between nutrient level and PFD.

**8.3.4b** *Alstonville district study*

The aim of this study was to determine whether leaf nutrient data could be used as an alternative to percent ground cover to indicate degree of crowding in macadamia orchards. The N area and P area data, which are sensitive to shading, were compared with the ground cover data.

**Table 8.2** Site by leaf age by position counts

| Site | Leaf age | Position | | | | |
|---|---|---|---|---|---|---|
| | | 1 | 2 | 3 | 4 | 5 |
| A | New | 6 | 6 | 6 | 5 | 5 |
| | Old | 6 | 6 | 6 | 6 | 6 |
| C | New | 6 | 6 | 6 | 6 | 6 |
| | Old | 6 | 6 | 6 | 6 | 6 |
| FPN | New | 5 | 6 | 6 | 6 | 6 |
| | Old | 6 | 6 | 6 | 6 | 6 |
| FPS | New | 0 | 0 | 0 | 2 | 4 |
| | Old | 0 | 0 | 5 | 4 | 4 |
| H | New | 4 | 6 | 6 | 4 | 5 |
| | Old | 6 | 6 | 6 | 6 | 6 |
| K97 | New | 0 | 0 | 1 | 2 | 5 |
| | Old | 6 | 6 | 6 | 6 | 5 |
| PG | New | 6 | 6 | 6 | 6 | 6 |
| | Old | 6 | 6 | 6 | 6 | 6 |
| Q | New | 5 | 5 | 2 | 5 | 5 |
| | Old | 6 | 6 | 6 | 6 | 6 |
| SR | New | 5 | 6 | 6 | 6 | 6 |
| | Old | 6 | 6 | 6 | 6 | 6 |
| VP7 | New | 2 | 5 | 6 | 6 | 6 |
| | Old | 2 | 6 | 6 | 6 | 6 |
| VPN | New | 6 | 6 | 6 | 6 | 6 |
| | Old | 6 | 6 | 6 | 6 | 6 |
| VPS | New | 6 | 6 | 6 | 6 | 6 |
| | Old | 6 | 6 | 6 | 6 | 6 |

The effect of site (12), leaf age (FEL = new, HOL = old) and tree sampling position (1-5) on N area, P area, N% and P% were determined. At the most crowded sites, severe crowding at the bottom of canopies meant that flush growth, and as a consequence new leaves and occasionally old leaves were absent from the lower sampling positions. This meant that there are 90 missing values resulting in the site by leaf age by position counts of Table 8.2. A linear mixed model analysis of these data were undertaken.

Table 8.3 provides the full model for these data. The table is divided into site.tree, sampling) position and site.tree position effects and these effects have been subdivided into their individual components. Note that *error == site.tree.leafage.position* in this case. The final column gives the degrees of freedom (df) for the fixed (F) terms in the model and the number of effects (ne) for the random (r), random lack of fit (RLOF) and random coefficient (RC)) terms. The degrees of freedom specify the number of estimable fixed effect parameters while each random (R, RLOF or RC) term provides a single variance (or covariance for RC) component (see Verbyla or *et al.* (1998) for details). For each interaction term, the interaction variance is assumed to be homogeneous, that is, the variability of the interaction effects does not differ by cell.

Generalised least squares estimation has been used for the fixed effects and best linear unbiased prediction (Robinson, 1991) has been used for the random effects. The restricted maximum likelihood (REML) method of variance component estimation (Patterson and Thompson, 1971) has been used. Wald type tests (Table 8.4, 8.5) have been used to assess the significance of the fixed effects and the random effects have been assessed using REML log likelihood ratio tests (see Verbyla *et al.* (1998) for details). All analyses have been undertaken using the Fortran program ASREML (Gilmour *et al.* 1996.)

**Table 8.3:** Outline of analysis of the Narea (Parea) data

| Source | Term | Fixed (F) or random (R/RLOF/RC) | df or ne |
|---|---|---|---|
| Mean | *intercept* | F | 1 |
| Site.tree | *site* | F | 11 |
| | *leafage* | F | 1 |
| | *site.leafage* | F | 11 |
| | *site.tree* | RC | 72 |
| | *site.leafage.tree* | RC | 144 |
| Position | *linear(position)* | F | 1 |
| | *dev(position)* | RLOF | 5 |
| Site.tree Position | *site.linear(position)* | F | 11 |
| | *site.dev(position)* | R | 60 |
| | *leafage.linear(position)* | F | 1 |
| | *leafage.dev(position)* | R | 10 |
| | *site.leafage.linear(position)* | F | 11 |
| | *site.leafage.dev(position)* | R | 120 |
| | site.tree.linear(position) | RC | 72 |
| | *(correlation)* | RC | |
| | *site.tree.dev(position)* | R` | 360 |
| | *site.leafage.tree.linear(position)* | RC | 144 |
| | *(correlation)* | | |
| | *error* | | |

Yield leaf nutrient correlations

Regressions were conducted between leaf nutrient characteristics at each canopy position and kernel yield recorded in 1997.

**Table 8.4** Wald tests and associated p-values for the terms in the final models for Narea, parea, N% and P%

| Term | Narea | | Parea | | N% | | P% | |
|---|---|---|---|---|---|---|---|---|
| | wald | p | wald | p | wald | p | wald | p |
| *Site* | 13.08 | <.001 | 10.48 | <.001 | 2.55 | <.01 | 3.64 | <.001 |
| *Leafage* | 6.92 | <.01 | 61.57 | <.001 | 14.85 | <.001 | 17.81 | <.001 |
| *Site.leafage* | 2.77 | <.01 | 2.88 | <.01 | 6.13 | <.001 | 4.24 | <.001 |
| *Linear(posn)* | 73.33 | <.001 | 29.02 | <.001 | 13.31 | <.001 | | |
| *Site.linear posn)* | 5.78 | <.001 | 2.38 | <.01 | 3.78 | <.001 | | |
| *Leafage.linear(posn)* | | | | | 6.46 | <.05 | | |
| *Site.leafage.linear(posn)* | | | | | 5.69 | <.001 | 4.45 | <.001 |

**Table 8.5** Estimated variance components for the significant random terms in the final models for Narea, parea, N% and P%

| | Estimated variance components x $10^{-4}$ | | | |
|---|---|---|---|---|
| Term | Narea | Parea | N% | P% |
| *Site.tree* | 0.0574 | 0.0031 | 6.4179 | 0.0864 |
| *Site.leafage.tree* | 0.1709 | 0.0022 | 4.0230 | 0.1082 |
| *Dev(posn)* | 0.1093 | 0.0004 | | |
| *Site.dev(posn)* | | | | |
| *Leafage.dev(posn)* | | | 1.8889 | 0.0052 |
| *Site.leafage.dev(posn)* | | | 2.1604 | 0.0601 |
| *Site.tree.linear(posn)* | | | 1.0153 | 0.0015 |
| *(correlation)* | | | 1.0371 | |
| *Site.tree.dev(posn)* | 0.5352 | 0.0023 | 0.5060 | |
| *Site.leafage.tree.linear(posn)* | | 0.0003 | | |
| *(correlation)* | | 0.0008 | | 0.0418 |
| *Error* | 1.3878 | 0.0056 | 32.7143 | 0.2830 |

## 8.4 Leaf parameters and kernel yield

Correlation analyses were conducted between leaf ages at positions 1-5 within the canopy and kernel yields using the pearson Product Moment correlation coefficient computed using Sigma Stat 2.0 (Fox *et al.* 1995). Nut-in-shell yields were measured at 6 blocks of 3 trees at each site (McFadyen and McConchie 1996), and multiplied by the average kernel recovery (percentage of NIS comprising kernel) of 100 NIS to derive estimates of kernel yields.

## 8.5 Results

### 8.5.1 *Alstonville study*

The regression analyses conducted on the autumn and spring data, SLW, N area and P area gave significant correlations with PFD (Table 8.6).

**Table 8.6.** Correlations ($r^2$) between leaf parameters and light (PFD) for macadamia cultivars at Alstonville in 1996

| Correlation | Leaf | Cultivar<br>781 | <br>660 | <br>344 |
|---|---|---|---|---|
| | | | Autumn | |
| SLWv PFD | FEL | 0.43* | 0.14* | |
| N area v PFD | | 0.42** | 0.24** | |
| P area v PFD | | 0.23** | 0.15* | |
| SLW v PFD | HOL | 0.31* | n.s. | |
| SLW v PFD | YTL | 0.53** | 0.20* | |
| N area v PFD | | 0.62** | 0.30** | |
| P area v PFD | | 0.32** | 0.25** | |
| | | | Spring | |
| SLW v PFD | FEL | 0.43** | 0.51** | 0.45** |
| N area v PFD | | 0.45** | 0.55** | 0.48** |
| P area v PFD | | 0.45** | 0.37** | 0.37** |
| SLW v PFD | HOL | 0.53** | 0.36** | 0.34** |
| N area v PFD | | 0.27** | 0.59** | 0.34** |
| P area v PFD | | 0.55** | 0.22** | n.s. |
| SLW v PFD | YTL | 0.57** | n.s. | 0.55** |
| N area v PFD | | 0.56** | n.s. | 0.39* |
| P area v PFD | | 0.59** | n.s. | n.s. |

SLW = specific leaf wt (wt per unit leaf area)
N area = amount N per unit leaf area
P area = amount P per unit leaf area
* = $P < 0.05$
* * = $P < 0.01$

There was a significant ($P < 0.01$, $r^2 = 0.36$) correlation between N% and PFD for HOL cv. 660.

In the combined autumn and spring analyses, cultivar effects were significant ($P < 0.05$) for P area and P% (Table 8.7).

**Table 8.7** Cultivar effects on leaf parameters, 1996

| Variable | Cultivar |  |  | l.s.d. |
|---|---|---|---|---|
|  | 344 | 660 | 781 | ($P = 0.05$) |
| SLW (mg/cm$^2$) | 14.7 | 17.5 | 17.9 | n.s. |
| N area (mg/cm$^2$) | 0.2246 | 0.2424 | 0.2446 | n.s. |
| P area (mg/cm$^2$) | 0.0156 | 0.0197 | 0.0162 | 0.0025 |
| N (%) | 1.45 | 1.38 | 1.37 | n.s. |
| P (%) | 0.136 | 0.114 | 0.090 | 0.040 |

Age effects were significant ($P < 0.05$) for all 5 leaf variables (Table 8.8).

**Table 8.8** Leaf age effects on leaf parameters, 1996

| Variable | Leaf |  |  | l.s.d. |
|---|---|---|---|---|
|  | YTL | FEL | HOL | ($P = 0.05$) |
| SLW (mg/cm$^2$) | 0.0158 | 0.0162 | 0.0181 | 0.0005 |
| N area (mg/cm$^2$) | 0.2210 | 0.2288 | 0.2617 | 0.0081 |
| P area (mg/cm$^2$) | 0.0189 | 0.0191 | 0.0135 | 0.0008 |
| N (%) | 1.38 | 1.39 | 1.43 | 0.04 |
| P (%) | 0.130 | 0.127 | 0.082 | 0.004 |

The oldest leaf had the highest ($P < 0.05$) SLW, N area and N% and the lowest ($P < 0.05$) P area and P%.

All 5 leaf variables were positively affected by PFD ($P < 0.001$). The $r^2$ values were < 0.59 and examples are presented for SLW, HOL, cv. 781 (Fig. 8.1), P area, HOL, cv. 781 (Fig. 8.2), N area, HOL, cv. 344 (Fig. 8.3), P%, HOL, cv. 660 (Fig. 8.4), and N%, HOL, cv. 660 (Fig. 8.5).

**Fig. 8.1** Regression between SLW of HOL, cv. 781 and PFD

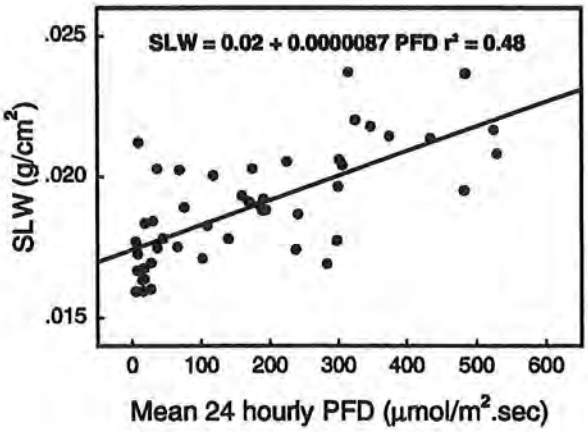


**Fig. 8.2** Regression between P area of HOL, cv. 781 and PFD

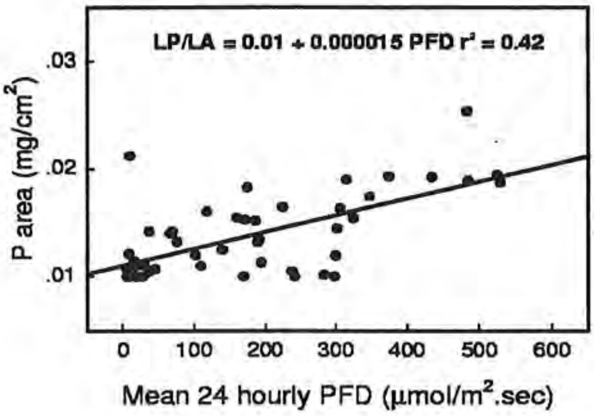


Fig. 8.3 Regression between N area of HOL, cv. 344 and PFD

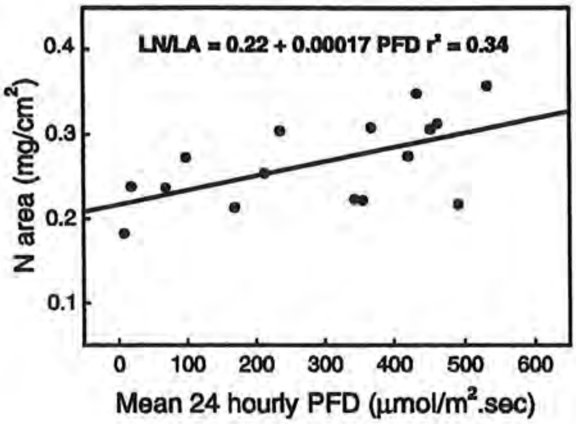


Fig. 8.4 Regression between P% of HOL, cv. 660 and PFD

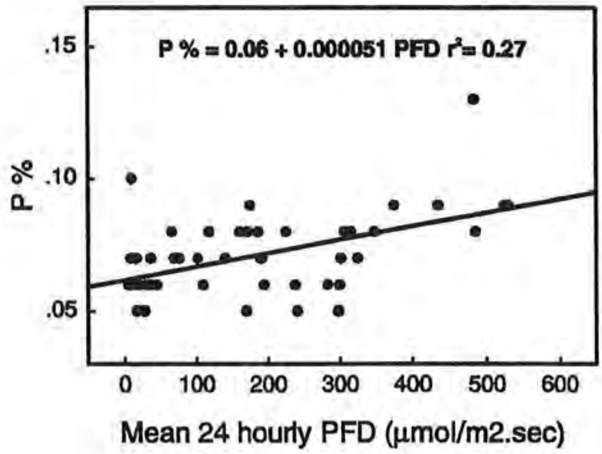
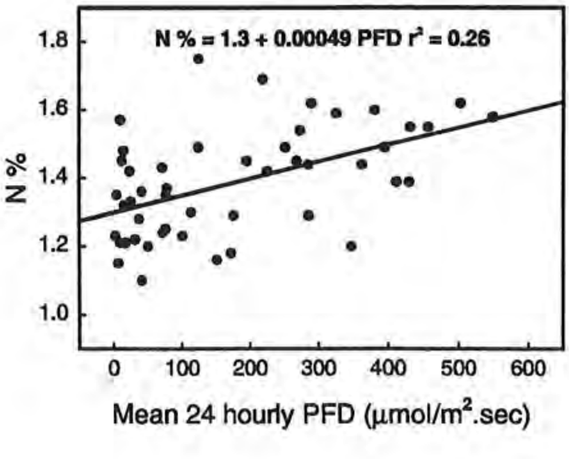


Fig. 8.5 Regression between N% of HOL, cv. 660 and PFD



### 8.5.2 *Alstonville district sites*

As leaf sampling position in the canopy increased from 1 (bottom) to 5 (top), PFD values increased by a factor of 1.3 in less crowded canopies to 17.9 in crowded canopies (Table 8.9).

Light measurements were recorded from mid October to early December on clear sunny days and the mean 24 hourly PFD values at the top of the canopy ranged from 450-600 µmol/m$^2$.sec across all sites. The decline in PFD values down the canopy was greater for N/S than E/W rows.

**Table 8.9** Cumulative 24 h Quantum sensor readings (µmol/m$^2$.sec) at 5 vertical positions in the tree for the 12 Alstonville district sites

| Site | Sensor position | | | | | Date sampled | Row orientation |
|---|---|---|---|---|---|---|---|
| | 1 | 2 | 3 | 4 | 5 | | |
| C | 3993 | 4619 | 6824 | 6833 | 12309 | 28 Oct | E/W |
| H | 6107 | 8136 | 8970 | 12215 | 11924 | 2 Nov | E/W |
| PG | 4119 | 4632 | 6239 | 12587 | 12456 | 9 Oct | N/S |
| Q | 8834 | 10724 | 10572 | 9787 | 11736 | 15 Oct | E/W |
| K97 | 5685 | 7302 | 11684 | 13865 | 14433 | 17 Dec | N/S |
| SR | 2979 | 2349 | 8202 | 10667 | 10919 | 29 Nov | N/S |
| FPN | 139 | 133 | 460 | 514 | 532 | 7Dec | N/S |
| VPN | 3339 | 3198 | 11034 | 12338 | 12761 | 7 Dec | N/S |
| VPS | 1628 | 3807 | 12335 | 11463 | 14067 | 24 Nov | N/S |
| A | 4583 | 8330 | 11766 | 14645 | 13661 | 2 Dec | E/W |
| VP7 | 1112 | 531 | 7469 | 11970 | 13241 | 27 Nov | N/S |
| FPS | 657 | 1080 | 3796 | 10941 | 11747 | 25 Nov | N/S |

The correlations between fitted N area, P area, N% and P% data at each tree position and the corresponding percent ground cover measurements are presented in Table 8.10.

**Table 8.10** Correlation coefficients between the fitted leaf nutrient means and the corresponding ground cover measurements

| Position | Narea | Parea | N% | P% |
|---|---|---|---|---|
| 1 | -0.603 | -0.449 | -0.269 | -0.202 |
| 2 | -0.548 | -0.490 | -0.164 | -0.184 |
| 3 | -0.465 | -0.463 | -0.092 | -0.246 |
| 4 | -0.260 | -0.383 | -0.062 | -0.226 |
| 5 | -0.201 | -0.378 | -0.173 | -0.065 |

There was a weak negative correlation, which decreased with increasing tree position.

The variables N area and P area were affected ($P < 0.05$) by site, leaf age, site x leaf age, linear (canopy position) and site x linear. Old leaves had higher N area values than young leaves and the rate of increase with canopy position was higher for old than new leaves and varied with site (Fig. 8.6). Phosphorus area differs depending on the site x leaf age combination (Fig. 8.7). There is an overall increase in P area with increasing canopy position and the rate of increase differs by site. For most sites, P area was higher for young than old leaves.

**Fig. 8.6** N area by sampling position for the 12 sites together with the fitted trend lines, old leaves (solid lines and o), new leaves (dashed lines and +)

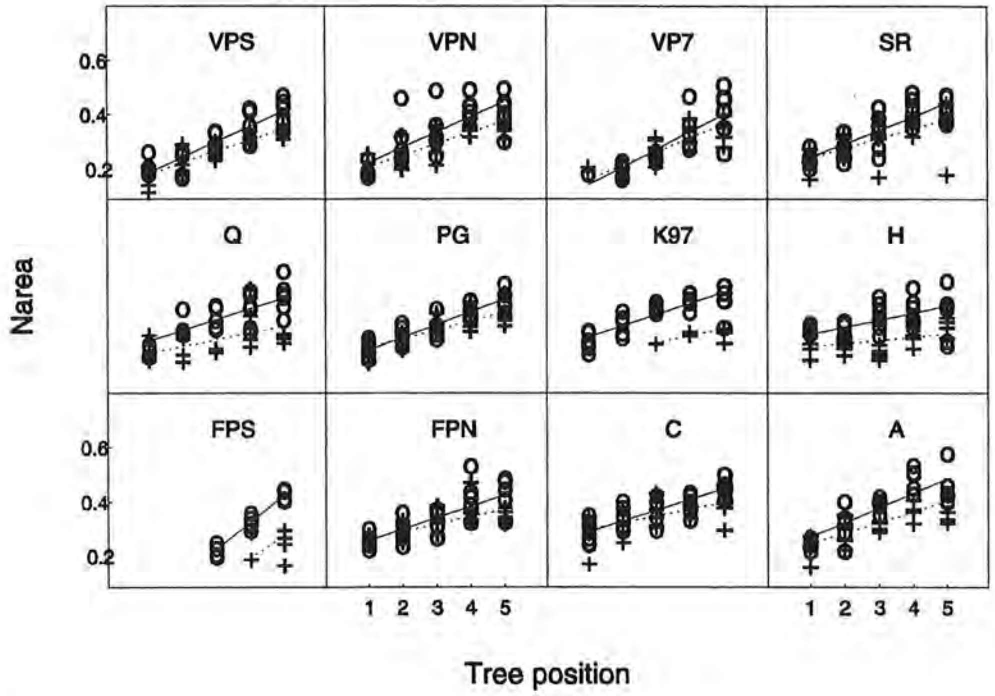


**Fig. 8.7** P area by sampling position for the 12 sites together with the fitted trend lines, old leaves (solid lines and o), new leaves (dashed lines and +)

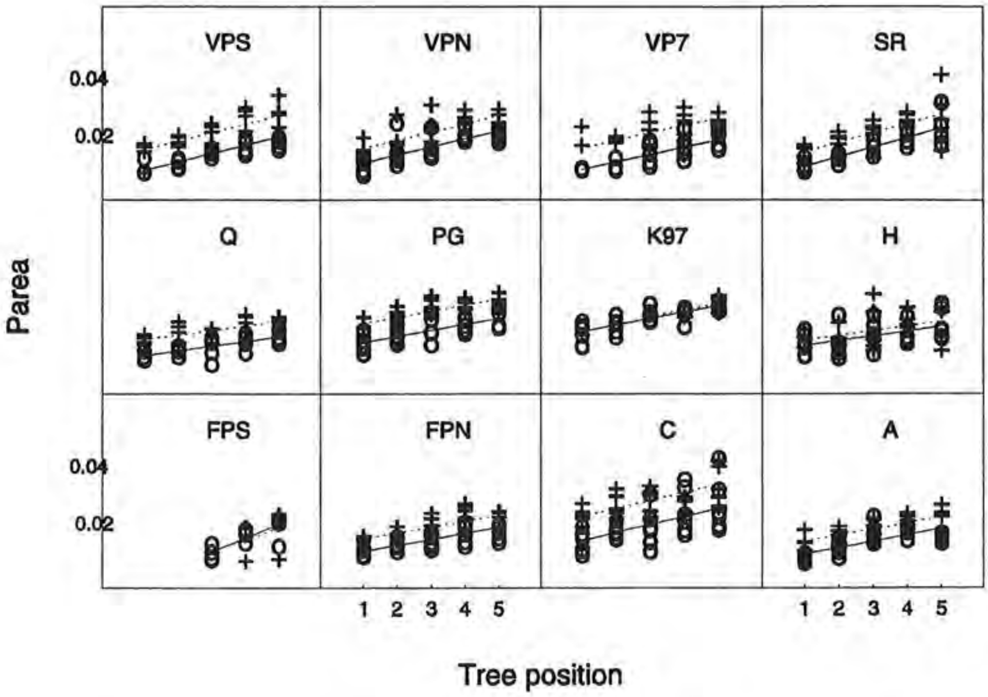
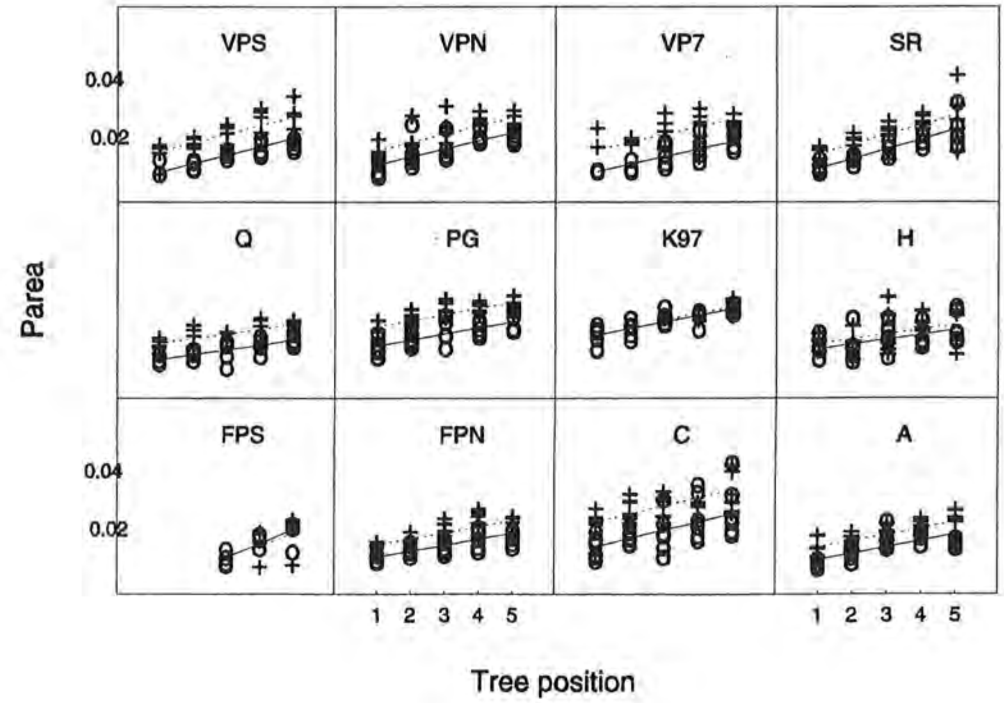


**Fig. 8.8** N% by sampling position for the 12 sites together with the fitted trend lines, old leaves (solid lines and o), new leaves (dashed lines and +)

The N% and P% in leaves were also affected ($P < 0.05$) by site, leaf age, site x leaf age. The N% was higher in old than new leaves and increased with canopy position. The rate of increase differed depending on the site x leaf



age combination (Fig. 8.8). At 2 sites, SR and K97, tree position had little effect on N% in new leaves. The P% was higher in new leaves than old leaves and was unaffected (*P* > 0.05) by canopy position (Fig. 8.9). However, P% was affected by the site x leaf age combination.

**Fig. 8.9** P% by sampling position for the 12 sites together with the fitted trend lines, old leaves (solid lines and o), new leaves (dashed lines and +)

The N concentrations in HOL across all sites ranged from 1.3-1.8% at position 1 and from 1.6-2.0% at the mid canopy position 3 (Table 11).

The corresponding values for P% were 0.06-0.11% at position 1 and 0.07-0.11% at position 3 (Table 8.12).

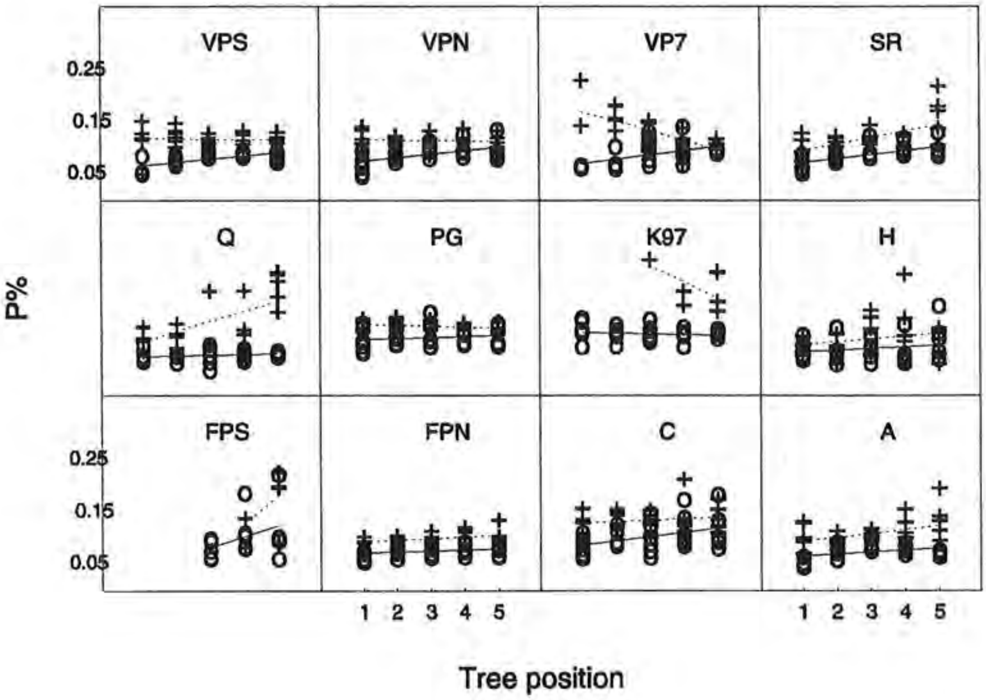


**Table 8.13.** Correlation coefficients (*P*<0.05) between leaf nutrient parameters for FEL (new leaves) and HOL (old leaves) at the 5 tree positions and kernel yield.

| Tree Position | N area | P area | N% | P% |
|---|---|---|---|---|
| | | FEL | | |
| 1 | -0.334 | 0.210 | n.s. | n.s. |
| 2 | -0.358 | -0.564 | n.s. | n.s. |
| 3 | n.s. | -0.442 | n.s. | -0.409 |
| 4 | n.s. | -0.326 | n.s. | n.s. |
| 5 | n.s. | n.s. | -0.343 | -0.493 |
| | | HOL | | |
| 1 | -0.316 | -0.645 | -0.399 | -0.673 |
| 2 | -0.409 | -0.605 | n.s. | -0.521 |
| 3 | n.s. | -0.275 | n.s. | n.s. |
| 4 | n.s. | -0.274 | n.s. | -0.298 |
| 5 | n.s. | -0.398 | n.s. | -0.351 |

The most consistent correlations between leaf parameters and kernel yield were for P% and P area (Table 8.13). The weak negative correlations indicated that there was some evidence of a reduction in yield with increasing P content of lower leaves. The N parameters either were very poorly or not correlated with yield.

**Table 8.11**. The fitted site x leafage x position N% means and their standard errors

| | | Canopy position | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|
| | | 1 | | 2 | | 3 | | 4 | | 5 | |
| site | Leafage | mean | se | mean | se | mean | se | mean | se | mean | se |
| VPS | Old | 1.392 | 0.085 | 1.515 | 0.065 | 1.638 | 0.061 | 1.761 | 0.073 | 1.883 | 0.096 |
| | New | 1.338 | 0.085 | 1.350 | 0.065 | 1.361 | 0.061 | 1.373 | 0.073 | 1.385 | 0.096 |
| VPN | Old | 1.477 | 0.085 | 1.610 | 0.065 | 1.743 | 0.061 | 1.875 | 0.073 | 2.008 | 0.096 |
| | New | 1.500 | 0.085 | 1.498 | 0.065 | 1.487 | 0.061 | 1.475 | 0.073 | 1.464 | 0.096 |
| VP7 | Old | 1.274 | 0.100 | 1.436 | 0.074 | 1.599 | 0.063 | 1.761 | 0.073 | 1.923 | 0.098 |
| | New | 1.632 | 0.102 | 1.591 | 0.076 | 1.550 | 0.063 | 1.508 | 0.073 | 1.467 | 0.098 |
| SR | Old | 1.637 | 0.085 | 1.724 | 0.065 | 1.812 | 0.061 | 1.899 | 0.073 | 1.986 | 0.096 |
| | New | 1.586 | 0.087 | 1.640 | 0.067 | 1.694 | 0.061 | 1.748 | 0.073 | 1.802 | 0.096 |
| Q | Old | 1.676 | 0.085 | 1.724 | 0.065 | 1.772 | 0.061 | 1.821 | 0.073 | 1.869 | 0.096 |
| | New | 1.516 | 0.090 | 1.718 | 0.070 | 1.919 | 0.064 | 2.121 | 0.077 | 2.323 | 0.101 |
| PG | Old | 1.660 | 0.085 | 1.734 | 0.065 | 1.807 | 0.061 | 1.881 | 0.073 | 1.955 | 0.096 |
| | New | 1.467 | 0.085 | 1.495 | 0.065 | 1.522 | 0.061 | 1.550 | 0.073 | 1.578 | 0.096 |
| K97 | Old | 1.753 | 0.085 | 1.758 | 0.065 | 1.764 | 0.061 | 1.769 | 0.074 | 1.775 | 0.098 |
| | New | NA | NA | NA | NA | 2.638 | 0.176 | 2.323 | 0.100 | 2.008 | 0.119 |
| H | Old | 1.721 | 0.085 | 1.691 | 0.065 | 1.660 | 0.061 | 1.630 | 0.073 | 1.600 | 0.096 |
| | New | 1.345 | 0.091 | 1.409 | 0.069 | 1.473 | 0.063 | 1.537 | 0.077 | 1.601 | 0.103 |
| FPS | Old | NA | NA | NA | NA | 1.608 | 0.097 | 1.891 | 0.079 | 2.174 | 0.115 |
| | New | NA | NA | NA | NA | NA | NA | 2.128 | 0.146 | 2.385 | 0.136 |
| FPN | Old | 1.599 | 0.085 | 1.649 | 0.065 | 1.699 | 0.061 | 1.749 | 0.073 | 1.799 | 0.096 |
| | New | 1.678 | 0.087 | 1.646 | 0.067 | 1.614 | 0.061 | 1.582 | 0.073 | 1.549 | 0.096 |
| C | Old | 1.769 | 0.085 | 1.800 | 0.065 | 1.832 | 0.061 | 1.863 | 0.073 | 1.894 | 0.096 |
| | New | 1.608 | 0.085 | 1.610 | 0.065 | 1.611 | 0.061 | 1.613 | 0.073 | 1.614 | 0.096 |
| A | Old | 1.708 | 0.085 | 1.810 | 0.065 | 1.912 | 0.061 | 2.014 | 0.073 | 2.115 | 0.096 |
| | New | 1.654 | 0.085 | 1.741 | 0.065 | 1.827 | 0.061 | 1.914 | 0.074 | 2.001 | 0.098 |

NA, leaves not available for sampling

**Table 8.12.** The fitted site x leafage x position P% means and their standard errors

| | | Canopy position | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|
| | | 1 | | 2 | | 3 | | 4 | | 5 | |
| site | Leafage | mean | se | mean | se | mean | se | mean | se | mean | se |
| VPS | Old | 0.061 | 0.009 | 0.067 | 0.007 | 0.073 | 0.007 | 0.079 | 0.009 | 0.085 | 0.012 |
| | New | 0.112 | 0.009 | 0.112 | 0.007 | 0.111 | 0.007 | 0.110 | 0.009 | 0.109 | 0.012 |
| VPN | Old | 0.069 | 0.009 | 0.076 | 0.007 | 0.082 | 0.007 | 0.089 | 0.009 | 0.096 | 0.012 |
| | New | 0.110 | 0.009 | 0.109 | 0.007 | 0.108 | 0.007 | 0.108 | 0.009 | 0.107 | 0.012 |
| VP7 | Old | 0.064 | 0.010 | 0.073 | 0.008 | 0.081 | 0.008 | 0.089 | 0.009 | 0.098 | 0.012 |
| | New | 0.164 | 0.010 | 0.146 | 0.008 | 0.127 | 0.008 | 0.109 | 0.009 | 0.091 | 0.012 |
| SR | Old | 0.066 | 0.009 | 0.074 | 0.007 | 0.081 | 0.007 | 0.089 | 0.009 | 0.097 | 0.012 |
| | New | 0.091 | 0.009 | 0.103 | 0.007 | 0.115 | 0.007 | 0.127 | 0.009 | 0.139 | 0.012 |
| Q | Old | 0.067 | 0.009 | 0.069 | 0.007 | 0.070 | 0.007 | 0.071 | 0.009 | 0.072 | 0.012 |
| | New | 0.097 | 0.009 | 0.116 | 0.008 | 0.135 | 0.008 | 0.155 | 0.009 | 0.174 | 0.012 |
| PG | Old | 0.100 | 0.009 | 0.102 | 0.007 | 0.104 | 0.007 | 0.106 | 0.009 | 0.108 | 0.012 |
| | New | 0.130 | 0.009 | 0.128 | 0.007 | 0.126 | 0.007 | 0.124 | 0.009 | 0.122 | 0.012 |
| K97 | Old | 0.114 | 0.009 | 0.113 | 0.007 | 0.111 | 0.007 | 0.110 | 0.009 | 0.108 | 0.012 |
| | New | NA | NA | NA | NA | 0.244 | 0.019 | 0.211 | 0.012 | 0.179 | 0.014 |
| H | Old | 0.077 | 0.009 | 0.080 | 0.007 | 0.083 | 0.007 | 0.086 | 0.009 | 0.089 | 0.012 |
| | New | 0.091 | 0.009 | 0.097 | 0.008 | 0.102 | 0.008 | 0.108 | 0.010 | 0.113 | 0.012 |
| FPS | Old | NA | NA | NA | NA | 0.076 | 0.011 | 0.097 | 0.010 | 0.118 | 0.014 |
| | New | NA | NA | NA | NA | NA | NA | 0.122 | 0.016 | 0.176 | 0.016 |
| FPN | Old | 0.066 | 0.009 | 0.068 | 0.007 | 0.069 | 0.007 | 0.071 | 0.009 | 0.073 | 0.012 |
| | New | 0.088 | 0.009 | 0.091 | 0.007 | 0.094 | 0.007 | 0.097 | 0.009 | 0.100 | 0.012 |
| C | Old | 0.081 | 0.009 | 0.089 | 0.007 | 0.097 | 0.007 | 0.105 | 0.009 | 0.113 | 0.012 |
| | New | 0.123 | 0.009 | 0.126 | 0.007 | 0.129 | 0.007 | 0.131 | 0.009 | 0.134 | 0.012 |
| A | Old | 0.059 | 0.009 | 0.063 | 0.007 | 0.067 | 0.007 | 0.071 | 0.009 | 0.075 | 0.012 |
| | New | 0.089 | 0.009 | 0.096 | 0.007 | 0.103 | 0.007 | 0.111 | 0.009 | 0.118 | 0.012 |

NA, leaves not available for sampling

## 8.6 Discussion

The availability of light throughout macadamia canopies affected SLW and leaf nutrient status and when expressed as N area or P area, the effects were more profound. Contrary to the general trend that N is allocated preferentially to young leaves (Traw and Ackerley 1995; Kitajima *et al.* 1997; Anten *et al.* 1998), mature 6-7 month old macadamia leaves (HOL) had the highest SLW, N% and N area. In contrast, P% and P area were higher in young leaves. Branching has also been suggested as the primary determinant of nutrient allocation within canopies (Lynch and Gonzalez 1993) and this is a feature of macadamia growth.

All macadamia sites were located on krasnozem soils which have high N availability, confirmed by Huett (1993) where on similar sites, high yielding tomato crops failed to respond to N fertiliser. The N demand by most vegetable crops is many fold higher than tree crops (Huett 1996).

DeJong *et al.* (1989) demonstrated that peach trees responded to N by increasing the N content and hence photosynthetic capacity of older, partially shaded leaves. The higher N content of mature macadamia leaves compared with young leaves would reflect high soil N availability and suggests that mature leaves have a major role in storing N. Leaves have a major role in the internal cycling of N in trees and mature leaves would seasonally store N for remobilisation during periods of active growth (Millard 1996).

The best correlations between PFD and leaf parameters had $r^2 \leq 0.59$ indicating that they may have potential as a leaf based shading indicator. This was supported by the wide range of PFD values between the top and bottom of canopies measured in district sites. The PFD gradient was most pronounced for the most crowded sites.

A major constraint in this study was the use of percent ground cover to estimate crowding because it lacked sensitivity above 80% ground cover. At this level of crowding, canopy volume decreases at the bottom of the tree and is not reflected in the ground cover measurement. At the most crowded site which had 95% ground cover, canopy was absent below a height of 7 m. The loss of lower canopy was also a constraint in developing a leaf based shading indicator where change in leaf parameter with tree height or canopy position was to be used. The leaf variables were only weakly correlated with percent ground cover and were therefore not appropriate alternatives. Further work is required to determine whether leaf based shading indicators are better correlated with more precise indicators of canopy crowding such as leaf area index.

The reduction in macadamia leaf N and P concentrations through shading means that the leaf nutrient status of a macadamia orchard will be affected by sampling protocol. Leaves sampled on the northern side of trees will have a higher N concentration than leaves sampled on the southern side and this effect will be most pronounced for trees running East-West and for more crowded orchards. Shading effects on leaf P concentration were les pronounced. The leaf sampling protocol advocated by Stephenson *et al.* (1988) should be modified to provide a more stable light environment. In older orchards this would require a higher sampling position in the tree to avoid excessive shading. In younger orchards, lower leaves would be more highly irradiated which on the basis of the current study would contain higher N and P concentrations.

The leaf age effects on P concentration support the current practice of standardising leaf type for diagnostic purposes for all crops (Reuter and Robinson 1997). While cultivar effects were recorded for leaf P concentration, the inclusion of cultivar in diagnostic standards may warrant further investigation. Seven of the 12 district sites recorded leaf P concentrations below the 0.08% standard with no evidence of a detrimental yield effect.

Stephenson and Gallagher (1989 a) suggested that n fertiliser can reduce macadamia nut yield by stimulating vegetative growth at the expense of reproductive growth. Inconsistent negative effects of excessive n fertiliser on macadamia nut in shell (NIS) yield were reported by Stephenson and Gallagher (1989 b). When these responses were reviewed for all horticultural crops, there was no experimental evidence to support a vegetative growth (Huett 1996).

A more recent study (Stephenson *et al.* 1997) showed an inconsistent weak negative correlation between yield and leaf N concentration (r= -0.64) which was not supported by the current study. We measured kernel yield, which better represents economic yield, and it was very poorly correlated with leaf N levels. The recent recommendations by Stephenson *et al.* (1997) that fertiliser N should be withheld until leaf N declined to 1.3% is not supported by the current study. At most of the 12 Alstonville district sites for an equivalent sampling position and leaf age, leaf N concentrations exceeded the most recent diagnostic adequate standards of 1.3-1.4% in HOL (Robinson *et al.* 1997). Leaf sampling protocols will markedly affect leaf N levels due to the effects of leaf age and shading and therefore leaf N analysis should be treated with caution when interpreting tree N status.

Leaf P concentrations at the 12 Alstonville district sites were around 0.06% in HOL at the lowest tree sampling position compared with the current adequate diagnostic range of 0.08 - 0.11% (Robinson *et al.* 1977). Where P was incorporated to a depth of 15 cm at rates up to 63 kg/ha P for cv. 344 on a krasnozem soil, leaf P concentrations varied from 0.06 - 0.08% (Firth and Vimpany 1995). The current diagnostic standards were developed by Stephenson and Cull (1986) using cvv.246 and 508. The current study demonstrated that in addition to leaf age and shading which affected leaf N levels, leaf P levels were also affected by cultivar. The current diagnostic P standards are of questionable value, particularly for cv. 344 where there was a weak negative correlation (P = -0.67) between leaf P concentration and kernel yield.

In the absence of reliable diagnostic leaf N and P standards, we conclude that leaf analyses have limited use in determining the nutritional status of macadamia orchards.

## 8.7 Acknowledgments

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# Chapter 9

# Investigation of sampling procedures to determine macadamia fruit quality in orchards.

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## 9.1 Abstract

Macadamia kernel quality estimates are of fundamental importance to understanding tree responses to many experimental treatments and orchard management protocols. Experimental measures of macadamia kernel quality, collected under field conditions, traditionally rely on the average of 100 fruit, sampled from the estimated peak in fruit drop. To detect changes in kernel quality over a single season, we measured variation in fruit quality of macadamia Cv. 344. To sample this variation we measured 10 fruit from 6 blocks of 3 trees at each of 7 sites, over 4 harvests made at monthly intervals. For all fruit collected we determined husk, shell and kernel dry weights; kernel recovery (the percentage of kernel to kernel and shell weight); and kernel specific gravity from which oil content was estimated. A split-plot analysis of variance model was used to determine variance estimates for each of the fruit quality parameters measured. The percentages of partitioned total variance of the quality parameters were lowest for sites (3.6-6.7%) intermediate for harvests (3.3-41.1%), and highest for fruit (32.9-71.2%). Using these estimates, we investigated the influence of varying the number of replicates per site and fruits per replicate on kernel quality estimates. The analyses indicated that samples of 5 fruit, from each of 6 randomly located blocks within a site, represent the minimum replication required to detect commercially relevant changes in the kernel quality parameters measured. Larger sample sizes and increased replication did not significantly increase the precision of estimates. This protocol uses fewer fruit, reduces labour inputs and produces increased precision of kernel quality estimates compared with existing techniques.

## 9.2 Introduction

*Macadamia integrifolia* and *M. tetraphylla* (Proteaceae) are evergreen species, endemic to the Australian rainforests of northern New South Wales and Southern Queensland (Johnson and Briggs 1975; Wrigley and Fagg 1991; Wagner-Wright, 1995). These species, and their hybrids, produce fruit with an edible kernel. Commercial production of macadamia kernel now represents Australia's third most valuable horticultural export, behind citrus and grapes (Australian Horticultural Corporation 1998). The key to the export success of Australian macadamia is the high quality of its kernel (McConachie 1996).

Australian macadamia harvesting practices collect fruit from the ground using mechanical or manual techniques (Mason and Wells 1984). The period of macadamia fruit abscission may last from one to several months (Gallagher et al. 1996; McConachie 1997). This necessitates several harvests during the season because macadamia kernel quality may deteriorate if left on the ground for periods greater than four weeks (Mason and Wells 1984).

Assessments of macadamia kernel quality for experimental and commercial purposes include the following measurements: kernel weight; kernel recovery (the percentage of kernel to kernel and shell weight); percentage first grade kernels (kernel comprising greater than 72% oil content, or specific gravity less than 1.0) (Ripperton et al. 1938; Moltzau and Ripperton 1939; Mason and Wills 1983; McConchie et al. 1996). To estimate macadamia kernel quality of either individual trees or orchards, researchers have variously used: a single sample collected from beneath individual trees (Ripperton, Moltzau and Edwards 1938) or 4 replicate trees (Stephenson et al. 1993) at estimated periods of peak fruit abscission; collections from beneath individual trees (Mason 1983; Mason and Wells 1984) or blocks of three trees (McFadyen and McConchie 1996); and single or multiple harvests from trees (Mason 1983; Mason and Wills 1983; Gallagher et al. 1997). Historically, samples used to assess kernel quality comprise 100 fruit (Hamilton, Mouat and Cameron 1964; Stephenson et al. 1993). Although validation of this sample size for detecting changes in macadamia kernel quality does not appear to have been done.

This paper investigates sampling methods for detecting changes in macadamia fruit and kernel quality on an orchard scale.

## 9.3 Materials and Methods

### *9.3.1 Study Sites*

Seven sites in the Alstonville district of northern NSW, Australia ($28^0 17'$ S $153^0 28'$ E) were selected for the examination of fruit quality. All study orchards were composed solely of the macadamia cultivar Hawaiian Agriculture Experimental Station 344 (344) grafted onto *M. integrifolia* seedling rootstocks. Sites varied in age between 9 and 17 years with planting densities ranging between 247 and 408 trees/ha.

### *9.3,2 Sampling strategy*

#### *9.3.2a Collection of fruit*

Six plots (replicates) of 3 trees each were randomly located at each of the 7 sites. In February, 4 weeks prior to the first harvest all fruit on the ground (prematurely abscised) were removed from each plot. There followed 4 harvests at monthly intervals in March, April, May and June 1997 when fruit on the ground were collected from each plot. Ten individual nuts were selected at random from amongst those with green husks (indicating abscission in the proceeding few days). Thus there were 4 harvests x 7 sites x 6 plots x 10 fruit = 1680 fruit samples.

### *9.3.2b Fruit processing*

Fruit were stored in a $-15^0$ C freezer following each collection, until completion of the last harvest. Then fruit were thawed and separated into component parts, namely: embryo (kernel); testa (shell), and; pericarp (husk). Each component was weighed, and dried in an oven over 6 days (two days at each of $37^oC$, $45^oC$ and $57^oC$) to obtain moisture contents of c. 1 – 2 % (Anon. 1995; Gallagher et al. 1997). Each component was re-weighed to obtain a dry weight. Individual kernel oil content was determined from the kernel specific gravity, after the method of Ripperton et al. (1938) and McConchie *et al.* (1996).

### *9.3.2c Statistical analysis*

The aim of the sampling strategy was to provide estimates of the average fruit quality for the entire crop from a given location. Therefore, to evaluate alternative sampling strategies, we calculated the standard error for each parameter using the complete set of data and for subsets with numbers of plots and numbers of fruits per plot varied. To estimate the standard errors, we constructed a split-plot analysis of variance table for each fruit quality parameter to reflect the strata in the trial, namely: fruit within harvest within replicates within sites. An abbreviated analysis of variance table is displayed in Table 9.1. Using estimates of variance derived from each of the split-plot ANOVA's, namely site.rep (Error A= Ea) and site.harvest.rep (Error B = Eb) (Table 9.2), we derived the standard error of a site mean for each parameter using equation (1) (Steele and Torrie, 1960).

$$\text{s.e. of fruit parameters about a site mean} = \sqrt{\frac{3*Eb+Ea}{f*r*h}} \qquad \text{(Equation 1)}$$

We subsequently simulated the impact of varying the number of replicates per site (r) and the number of fruits per replicate (f) on these standard errors. As an example of the simulation, we set the number of harvests to 4. The analysis also allowed us to assess the proportion of total variation in fruit quality due to each sampling level of the experiment (Table 9.3).

## 9.4 Results

### *9.4.1 Sampling strategy*

We calculated the predicted standard error of a site mean (s.e.(site mean)) for each quality parameter. We calculated the s.e.(site means) by substituting into equation (9.1): 1-20 fruit for each of 1, 3, 6 and 10 replicates per site. Graphs of the results are presented in Figure 9.1. These graphs illustrate the large gains in precision from increasing the number of fruits in each replicate. Over all quality parameters, the level of precision for a given amount of replication was close to optimum at five fruits per replicate. Gains in the precision of, for example, kernel recovery (Figure 9.1d) between sampling 1 and 5 fruit per block, in each of 4 harvests, represent a reduction of 39% in the standard error of a site mean. Increasing fruits sampled from 5 to 10 per plot produced only a 5% further reduction in the standard error of kernel recovery per site which was not significantly lower at the $p < 0.05$ level. Increasing the number of replicates per site also resulted in increased precision on a site mean. However, the predictions indicated that the gains in precision would not be significant ($p < 0.05$) when more than six replicates were sampled.

### *9.4.2 Variation between fruits, reps, sites and harvests*

Variation in oil content was mostly due to fruit to fruit variability while variation in shell weight was mostly due to harvests (Table 9.3). Variation between sites and between replicates within sites accounted for a moderate amount (3.6-6.7%) of the total variation in each parameter and was comparable across parameters.

### *9.4.3 Spatial variability within orchards*

Replicates within sites did not account for a large amount of variation in quality parameters (Table 9.2). However, the Best-Linear-Unbiased-Predictors (BLUPS) of the replicate effects within each site at each harvest demonstrated that it is still important to obtain adequate spatial coverage of each site if the means are to be unbiased. The BLUPs of the replicate effects on each quality parameter were obtained from the ANOVA model. The husk weight BLUPS are presented as bar charts in Figure 9.2. The average husk weights ranged from 1.7 g to 2.4 g. This level of variance demonstrates that attempts to represent a site by sampling from only one location, or at a particular harvest, could result in a site mean that is biased by as much as 0.3 g, or 12 to 17% of the site mean for fruit husk weight.

## 9.5 Discussion

This work has described a sampling protocol suitable for the assessment of fruit quality in macadamia Cv. 344 orchards. The sites from which we obtained samples all occurred in the same geographic area. The results show that variation arises from differences between fruits and between harvests and to a lesser extent to variation within and between sites. It is suggested that at least 5 fruits be randomly sampled from each of 6 blocks within an orchard at each harvest to adequately sample fruit quality within a single season. It should be noted that this sampling protocol is distinct from the assessment of consignment quality received by processors. Those consignments frequently contain nuts from several orchards, planting blocks and cultivars. Sampling for assessment of commercial quality is discussed by Mason (1991).

Researchers have used a range of sampling protocols to assess macadamia kernel quality, chemical and fatty acid composition, or the influence of kernel processing and storage on consumer acceptability (Lathrop 1925; Jones 1937; Ripperton, Moltzau and Edwards 1938; Cavaletto et al. 1966; Mason and Wells 1984). Frequently these protocols combined and bulk processed between 25 and 100 fruit (Storey 1960; Stephenson et al. 1993; Anon. 1995; McFadyen and McConchie 1996; Gallagher et al. 1997) from a single harvest either from the tree (Gallagher et al. 1997) or from the ground. (Stephenson et al. 1993; McFadyen and McConchie 1996). On-farm decision support systems may use similar sampling protocols to determine industry best practices (Newett et al. 1996; Newett and Mulo 1996; Anon. 1998). In future, there would seem to be benefits of incorporating statistically based sampling protocols into macadamia research to increase both the resolution and predictive quality of the information produced.

The observed level of inter-site variation in the kernel quality of a single cultivar endorses the requirement for replication of sites within an area. However, this does not indicate that all cultivars will respond similarly to 344 over a range of sites. Therefore there is a requirement to validate our sampling recommendations for 344, and other cultivars, in geographically and environmentally disparate regions.

We measured fruit quality from clonally propagated 344 trees that exhibited up to 17% deviance from a site mean for a particular quality parameter. This indicates strong positional influences on macadamia fruit quality within an orchard. Thus the performance of a single tree within an orchard may not be representative of that genotype. If kernel quality is used to measure a treatment response, this result has broader implications for experiments investigating macadamia physiology, including studies of nutrition, irrigation, pruning, planting density and cultivar selection.

This study identified recently abscised fruit for sample harvests by the green colour of the husk. The fruit collected were therefore in contact with the ground for only a short time. Commercial harvests, by contrast, collect fruit from the ground at intervals ranging from a week to a month (Hamilton and Storey 1956; Stephenson and Trochoulias 1994). Consequently fruit may be in contact with the soil for hours, days or even weeks before harvest. If fruit are exposed to inclement weather, such as heavy rainfall during this time, germination, fungal infection or rancidity may reduce kernel quality (Nagao and Hirae 1992). Hence fruit in contact with the ground for extended periods may exhibit greater variation than we measured. However, Mason (1983) and Mason and Wells (1984) observed no decline in kernel quality for fruit in contact with the ground for periods of 4 weeks exposed to unspecified weather conditions. Their results would tend to confirm that kernel quality measurements of green nut-in-husk (NIH) are comparable to commercial kernel quality. Using our sampling protocol, it would be worthwhile to examine the level of variation in kernel quality parameters for fruit in contact with the ground for periods of up to and greater than a month.

Frequently 100 macadamia nuts are machine cracked to ascertain an average commercial, or experimental fruit quality (Anon. 1995; Stephenson et al. 1993). We used hand cracking in preference to machine cracking since we considered it produced fewer fragments of either shell or kernel. These fine pieces of nut are frequently arbitrarily discounted and consequently could influence estimates of fruit quality. We concluded that 5 hand-cracked nuts per replicate provided near maximum precision of kernel quality estimates. Provided that the small mass loses resulting from machine-cracking can be accounted for, sample sizes of 5, or more, machine-cracked macadamia nuts should provide precise kernel quality estimates.

This paper has concentrated on developing a statistically based sampling procedure for assessing macadamia fruit quality. It provides the basis for detecting changes in macadamia fruit quality associated with on-farm influences. The work does not relate on-farm measures of quality with the influences of: kernel storage; value-adding processes; and consumer perceptions. The relationships between on-farm and in-factory measures of product quality warrant further investigation.

## 9.6 Acknowledgments

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## 9.7 Figures

**Figure 9.1.** Standard error of the site mean of the following macadamia fruit parameters associated with increasing numbers of replicates taken per site, and fruit numbers per replicate: a) Husk dry weight, b) Kernel oil content, c) Kernel dry weight, and d) Kernel recovery.

One replicate = solid line, three replicates = medium dashed line, six replicates = dotted line, ten replicates = dash-dot-dot-dash line.

**Figure 9.2.** The best linear unbiased prediction (BLUP) of deviation from the mean site macadamia husk dry weight measured in one orchard, for each replicate at each of 4 harvests.

We have denoted each graph by the number of the harvest, from 1-4.

Figure 9.1

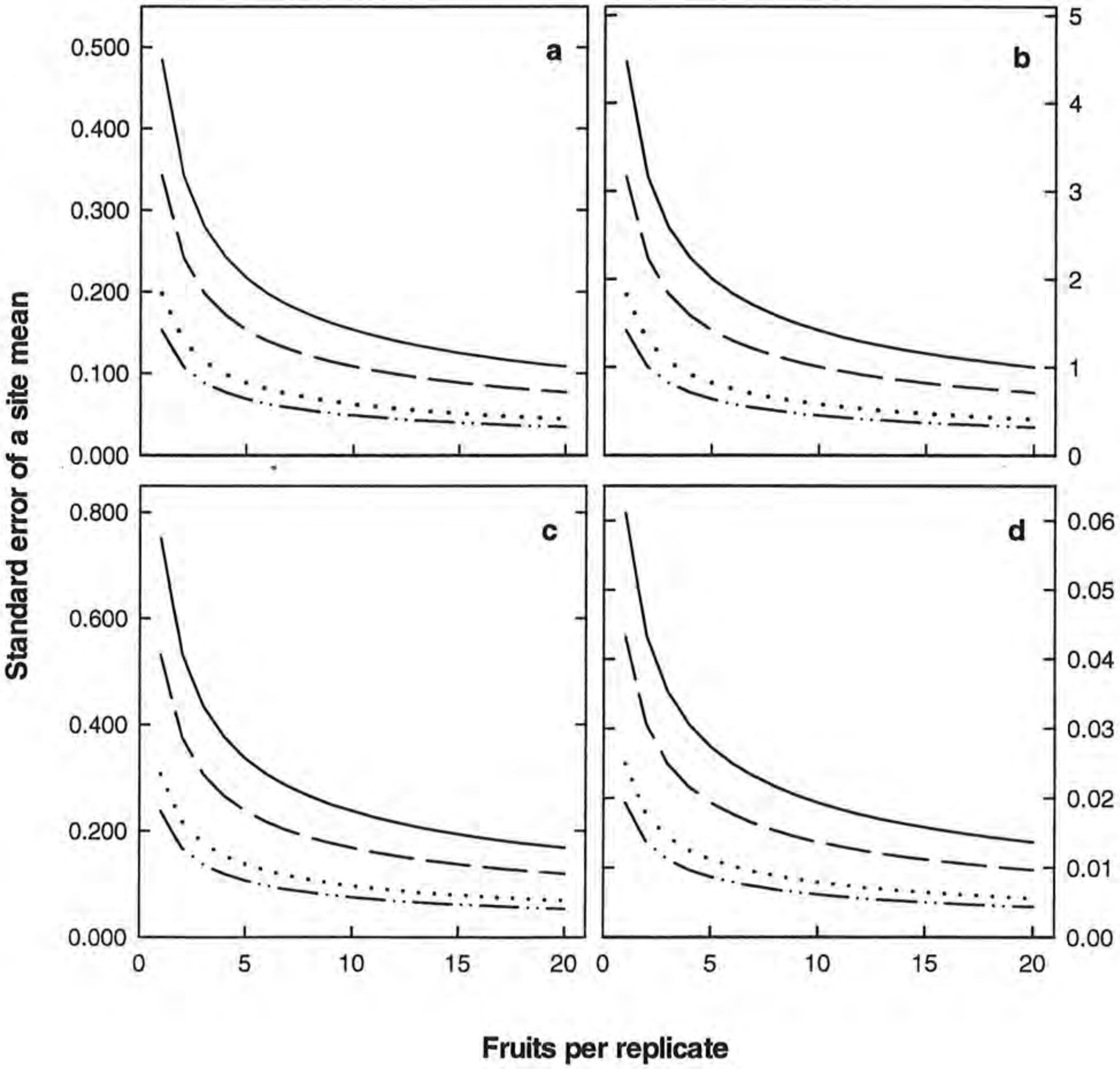
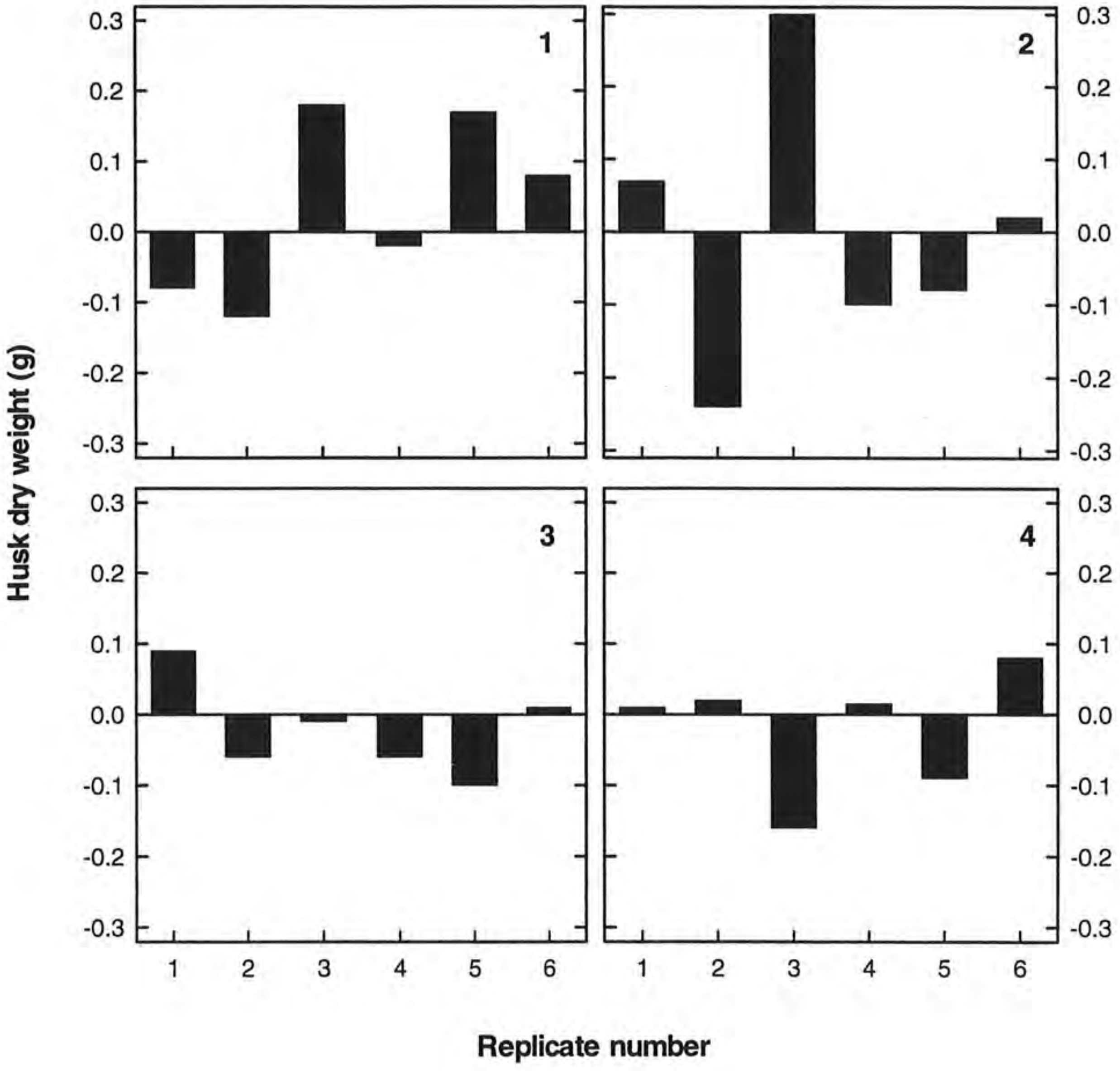

a
b
c
d
0.500
0.400
0.300
0.200
0.100
0.000
0.800
0.600
0.400
0.200
0.000
5
4
3
2
1
0
0.06
0.05
0.04
0.03
0.02
0.01
0.00
0
5
10
15
20
0
5
10
15
20
Standard error of a site mean
Fruits per replicate

Figure 9.2


1
2
3
4
0.3
0.2
0.1
0.0
-0.1
-0.2
-0.3
Husk dry weight (g)
1 2 3 4 5 6
Replicate number

## 9.8 Tables

### Table 9. 1

The basis of the ANOVA table used to assess the influence of harvest, site, and replicate on macadamia husk, shell and kernel dry weight, kernel recovery, and oil content from seven sites, at each of four harvests.

| Term | d.f. | |
|---|---|---|
| Sites | (s-1) = | 6 |
| Site.Rep (Error A) | S(r-1) = | 35 |
| Harvest | (h-1) = | 3 |
| Site.Harvest | (h-1)(s-1) = | 18 |
| Site.Rep.Harvest (Error B) | s(r-1)(h-1) = | 105 |
| Fruits | s.h.r.(f-1) = | 1512 |

**Table 9. 2**

Variance component estimates for error terms associated with the split-plot analysis of variance table described in Table 1, for each of the macadamia fruit parameters measured.

|  | Parameters |  |  |  |  |
|---|---|---|---|---|---|
| Source of variance | Husk d/w | Shell d/w | Kernel D/w | Kernel recovery | Oil content % |
| Error A | 0.426 | 1.187 | 0.827 | 0.006 | 21.222 |
| Error B | 0.171 | 1.123 | 0.478 | 0.003 | 19.680 |

**Table 9. 3**

Percent of total variance in each fruit quality parameter due to each factor examined by the ANOVA model.

| | Parameters | | | | |
|---|---|---|---|---|---|
| Source of variation in macadamia fruit parameters measured | Husk d/w | Shell d/w | Kernel d/w | Kernel recovery | Oil content % |
| Site | 3.6 | 4.7 | 3.6 | 6.7 | 4.2 |
| Site.Rep (Error A) | 5.4 | 3.3 | 4.6 | 5.7 | 3.6 |
| Harvest | 26.0 | 41.1 | 21.4 | 14.6 | 3.3 |
| Site.Harvest | 8.0 | 12.1 | 4.6 | 8.0 | 7.8 |
| Site.Harvest.Rep (Error B) | 6.5 | 5.9 | 7.9 | 9.0 | 10.0 |
| Fruit | 50.6 | 32.9 | 57.9 | 56.0 | 71.2 |

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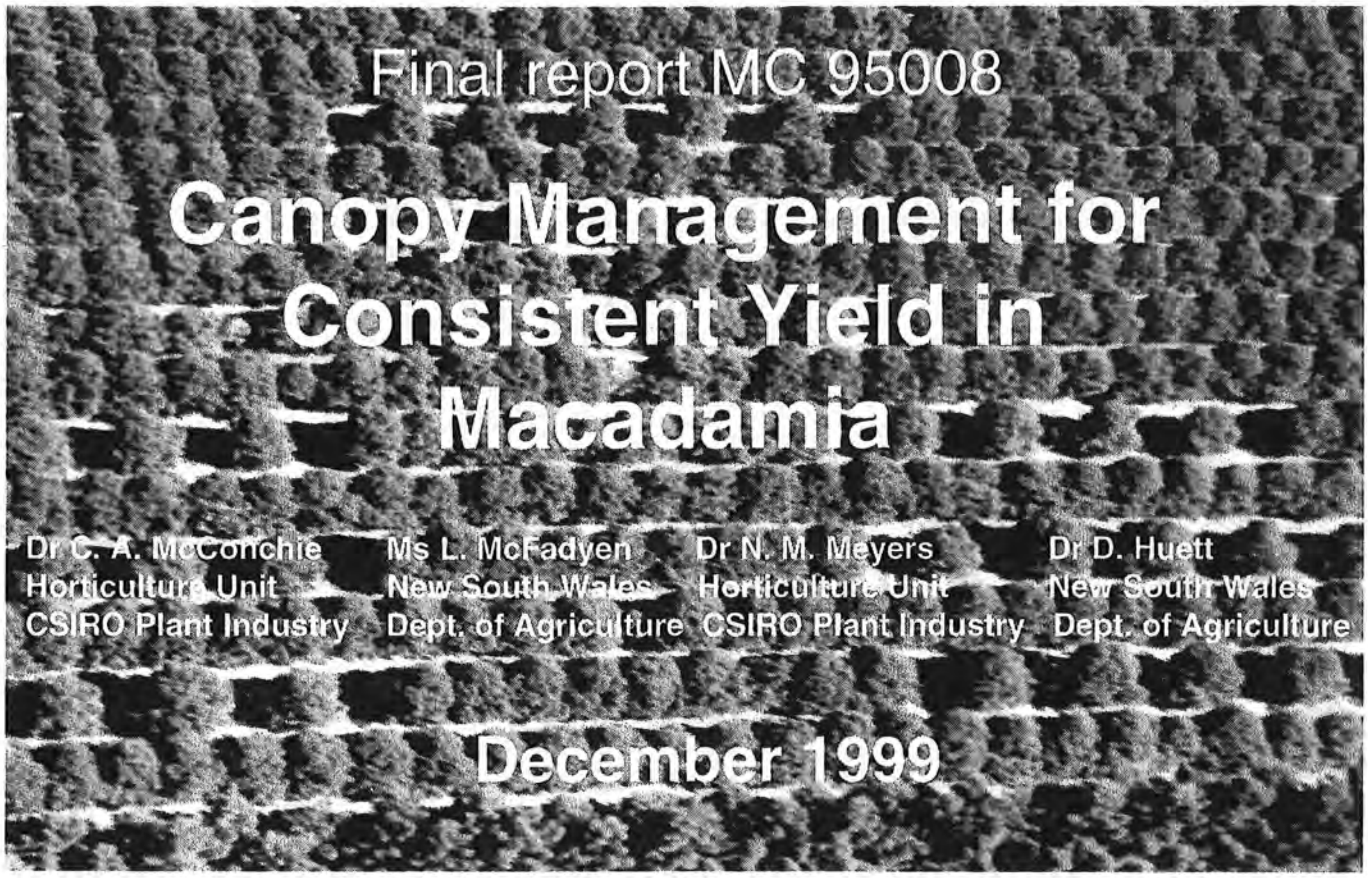

Final report MC 95008

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December 1999

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