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Yield responses to ethephon for unshaken and mechanically shaken macadamia

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Abstract. Ethephon promotes fruit abscission and accelerates harvest of macadamia, *Macadamia integrifolia* (Proteaceae), but has limited use due to concerns that associated abscission of inner-canopy leaves may reduce subsequent yield and nut quality. Yield and quality were monitored for 2 years following ethephon application to both unshaken and mechanically shaken trees of the late-abscising cultivar, A16. Nut quality was not adversely affected in subsequent seasons, but effects on yield varied. In 3 of 6 experiments, ethephon reduced yield in the year after application. However, in 4 of the 6 experiments, 2 years of ethephon application greatly elevated yield in the third year. This was not a compensating recovery from low second-year yield, as third-year yield of trees that received only 1 ethephon treatment did not differ from yield of control trees. Ethephon-assisted harvest remains feasible for macadamia, although further work is warranted given the potential risks and considerable benefits for subsequent yield. Inner canopy defoliation, resulting from ethephon use, could represent a canopy management technique for dense-canopy fruit trees.

Introduction

Promotion of macadamia fruit abscission, particularly for late-abscising cultivars, has potential to lower costs associated with prolonged harvesting, minimise deterioration of kernels on the ground and in the tree, and reduce environmental impacts associated with soil disturbance. Macadamia fruit abscission can be accelerated using the ethylene-generating compound, ethephon [(2-chloroethyl)phosphonic acid] (Kadman and Ben-Tal 1983; Gallagher and Stephenson 1985; Trochoulias 1986; Nagao and Sakai 1988; Richardson and Dawson 1993; Penter *et al.* 2002; Trueman *et al.* 2002), and fruit shedding can also be achieved by mechanical tree shaking (Gillespie *et al.* 1975; Nagao and Hirae 1992; Trueman *et al.* 2002). Kernel oil accumulation is generally completed before natural fruit abscission (Jones 1937, 1939; Liang and Myers 1975; Baigent 1983), and by several months before abscission for late-abscising cultivars such as 'Hidden Valley A16' (A16) in Australian orchards (McConchie *et al.* 1996; Trueman *et al.* 2000). Ethephon application or tree shaking therefore allow early harvest, with little or no effect on crop quality (Trueman *et al.* 2002).

However, ethephon application also causes leaf abscission (Kadman and Ben-Tal 1983; Gallagher and Stephenson 1985; Nagao and Sakai 1986; Trochoulias 1986; Richardson and Dawson 1993; Trueman *et al.* 2002) and has not been widely practiced due to concerns that future yield and crop quality may be adversely affected. Leaf loss following ethephon application occurs primarily inside the canopy, with young outer leaves less affected (Nagao and Sakai 1986; Trueman *et al.* 2002). Leaf drop was considered non-excessive by Gallagher and Stephenson (1985), who reported no effects on yield in the following year for cv. 'Own Choice', even with high ethephon rates (Stephenson and Gallagher 1987).

In this study, ethephon effects on yield and nut quality were monitored for 2 subsequent years for cv. A16 trees used by Trueman *et al.* (2002). Three experiments involved unshaken trees, and 3 experiments involved trees that were mechanically shaken 1 week after ethephon application.

Materials and methods

Original ethephon treatments

Trees of cv. A16, about 7 years old, were selected in a commercial orchard at Winfield, Queensland, Australia (24°32′S, 152°01′E) in 1998 (Trueman *et al.* 2002). Forty trees were used for each of 6 experiments, consisting of 8 trees in each of 5 rows, with each row regarded as a block. Treatments were allocated randomly in a 2 × 2 × 2 factorial design to the 8 trees in each row. Treatments consisted of spraying the whole tree with a solution of ethephon (Rhône-Poulenc) either at 0 or 1200 mg/L deionised water, to which was added either wetting agent (0.05% v/v Agral 600) (ICI) or drying retardant (glycerol), at either pH 2.0 or pH 7.0. Treatments were applied before natural abscission had commenced ('pre-season'), at the commencement of abscission ('early season') or during abscission ('mid-season'). Two experiments were performed at each stage, one utilising unshaken trees and the other utilising trees that were shaken using an EnviroHarvester tree shaker (Graham Grove Enterprises, Lismore, New South Wales) 1 week after spraying. Henceforth, reference to individual experiments is based on these original treatments (e.g. 'early season experiment on unshaken trees').

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Ethephon effects on subsequent crop

The type of additive did not affect fruit removal force or fruit abscission in 1998 (Trueman *et al.* 2002), and so yield and nut quality were monitored only in 1999 and 2000 for trees sprayed with solutions containing the wetting agent, Agral 600 (i.e. 20 trees per experiment, 120 trees total). Fruits were harvested from the ground and dehusked using a commercial dehusker that excluded non-commercial small nuts (<19 mm diameter). Nuts were then dried in fan-forced laboratory ovens at 45°C for 6 days. Unsound nuts were removed and excluded from the analyses. Total nut-in-shell (NIS) weights were recorded for all samples and total tree yield was calculated. Harvest dates for 1999 were 26 May, 6 July, 9 August and 7 September. Harvest dates for 2000 were 13 April, 16 May, 6 June, 12 July, 10 August, 5 September and 26 September.

From each sample, 5 nuts were cracked and weighed to determine NIS and kernel weights, kernel recovery and kernel oil content using methods described by McConchie *et al.* (1996) and Trueman *et al.* (2002). An average NIS weight, kernel weight, kernel recovery and kernel oil content, weighted according to the NIS yield of each harvest (Trueman *et al.* 2002), were then calculated for each tree in each year.

A subset of trees was used to assess yield and quality following 2 successive years of ethephon application. Within each block, 1 of the 2 trees sprayed with ethephon and Agral 600 in 1998 was selected randomly and re-sprayed on 1 July 1999 (i.e. mid-season) with ethephon at 1200 mg/L with 0.05% v/v Agral 600 at pH 2. Solution pH generally did not affect fruit removal force, crop removal or nut quality in 1998 (Trueman *et al.* 2002) and was therefore disregarded during random allocation of trees for re-spraying with ethephon in 1999. All unshaken trees from 1998 were left unshaken in 1999, and all shaken trees from 1998 were re-shaken on 6 July 1999. To facilitate harvest completion, all trees were shaken on 11 July 2000 and 10 August 2000, except for trees from the unshaken pre-season experiment, which were required for a longer-term study of effects of tree shaking.

The 6 experiments were analysed separately as some different rows had to be used for each experiment, and treatments on unshaken and shaken trees were originally applied on different dates. All results were analysed using random block analyses of variance, regarding rows as blocks. Where significant differences were detected, l.s.d. comparisons were performed. Means are reported with standard errors.

Results

Yield of control trees was generally lower in the year following the original sprays, possibly due to heavy rainfall during the flowering period of cv. A16 at the experimental site. The combined mean for control trees fell from 7.98 ± 0.20 kg in 1998 to 3.60 ± 0.30 kg in 1999 (n = 60). Ethephon caused significant further reductions in yield for 3 of 6 experiments (Fig. 1). This was evident in 2 experiments on unshaken trees (2.15 ± 0.74 *v.* 3.88 ± 0.77 kg, pre-season experiment; and 0.47 ± 0.11 *v.* 2.86 ± 0.69 kg, mid-season experiment) and in 1 experiment on shaken trees (2.89 ± 0.61 *v.* 4.91 ± 0.87 kg, early season experiment) (P<0.05).

Yield of control trees recovered somewhat in the third year, 2000 (5.75 ± 0.46 kg, n = 60). Yield of trees treated only in the first year with ethephon did not differ significantly from that of control trees (Fig. 2). However, trees that were ethephon-treated in both the first and second year produced significantly higher yield than controls in 4 of 6 experiments. Their yield was significantly higher in the pre-season and early season experiments on unshaken trees (9.92 ± 1.61 *v.* 6.76 ± 1.09 kg, and 10.08 ± 1.16 *v.* 3.90 ± 1.12 kg, respectively). It was also significantly higher in the pre-season and early season experiments on shaken trees (10.59 ± 1.23 *v.* 5.50 ± 1.03 kg, and 10.85 ± 1.00 *v.* 6.09 ± 1.11 kg, respectively) (P<0.05).

No significant (P>0.05) treatment differences were detected for combined yield of the second and third years, although trees that were ethephon treated in both first and second year provided the highest mean in all 6 experiments (Fig. 3).

Nut size and quality in each of the second and third years (data not shown) were not significantly affected by ethephon,

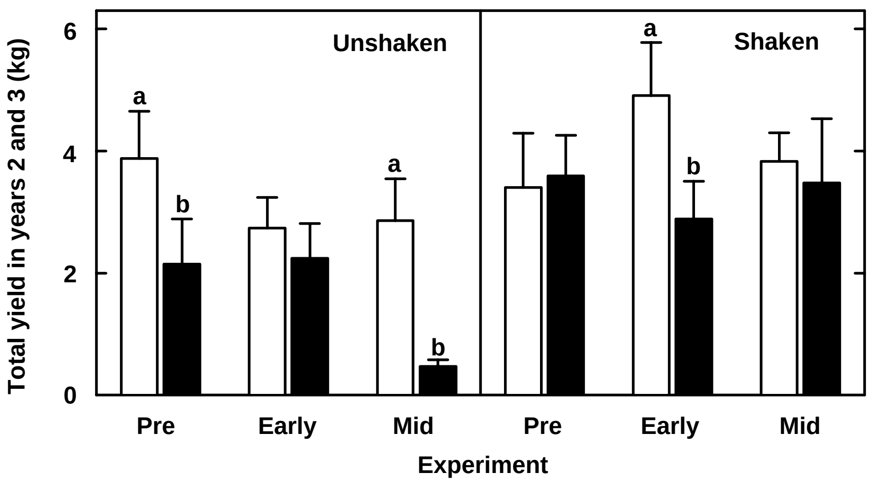

Figure 1. Yield of macadamia cv. A16 trees 1 year after application of ethephon at 1200 mg/L (open bars, control trees; closed bars, ethephon-treated trees). Six separate experiments were conducted: original sprays were applied at 3 different stages of the harvest season (pre-season, early season or mid-season), using either unshaken trees or trees shaken 1 week after spraying. Significant (P<0.05) differences between 2 means (± s.e.) are indicated by different letters (n = 10 trees).

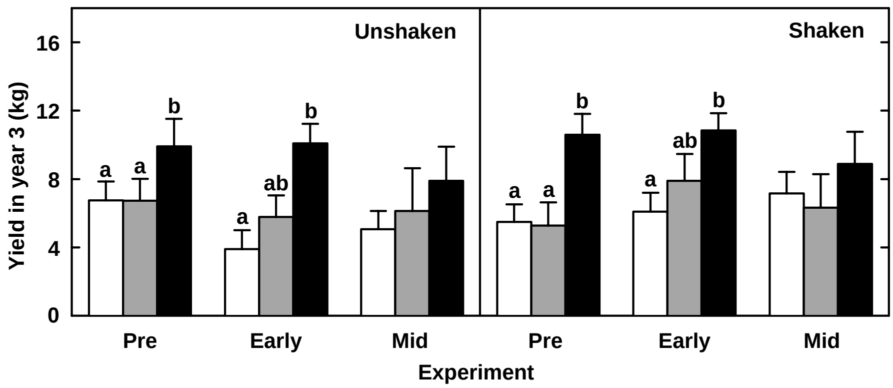

Figure 2. Yield of macadamia cv. A16 trees 2 years after original application of ethephon at 1200 mg/L (open bars, control trees; shaded bars, trees were ethephon treated in the 1st year; closed bars, trees were ethephon treated in the 1st and 2nd years). Six separate experiments were conducted: original sprays were applied at 3 different stages of the harvest season (pre-season, early season or mid-season), using either unshaken trees or trees shaken 1 week after spraying. Significant (P<0.05) differences among 3 means (± s.e.) are indicated by different letters (n = 5 trees for ethephon treatments, n = 10 trees for control).

except in the following case. In the pre-season experiment on shaken trees, kernel recovery in the third year was higher for trees treated with ethephon for 2 years (44.6 ± 0.7%) than for control trees (42.0 ± 0.6%) or trees treated with ethephon once only (41.5 ± 0.4%) (P<0.05). NIS and kernel weights were higher in the year with low yield, 1999 (range of means 8.31–9.00 g and 3.54–3.73 g, respectively), than in years with higher yield, 1998 (6.75–7.32 and 2.96–3.22 g, respectively; Trueman *et al.* 2002) and 2000 (6.14–7.70 and 2.70–3.27 g, respectively). Mean oil contents varied very little across the 3 years (1998: 79.3–80.1%; 1999: 80.0–80.6%; 2000: 79.1–80.9%).

Because ethephon generally had no effect on nut size or quality in either year, only combined second and third year means are presented (Tables 1 and 2). Two years of ethephon application reduced kernel weight in the pre-season experiment on unshaken trees (Table 1), but increased kernel recovery in the pre-season experiment on shaken trees (Table 2) (P<0.05). No other significant differences were evident. In all experiments, mean oil contents greatly exceeded the 72% oil content required for 'Grade 1' industry-standard kernels.

Discussion

Abscission of mature macadamia cv. A16 fruits can be accelerated using ethephon, either alone or as a fruit-loosening agent before mechanical tree shaking (Trueman *et al.* 2002). Current results show that ethephon

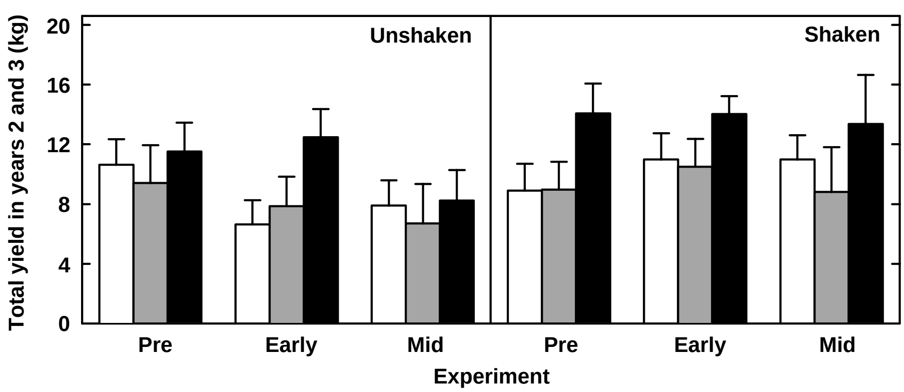

Figure 3. Combined yield (mean ± s.e.) of macadamia cv. A16 trees for the 2 years after original application of ethephon at 1200 mg/L (open bars, control trees; shaded bars, trees were ethephon treated in the 1st year; closed bars, trees were ethephon treated in the 1st and 2nd years). Six separate experiments were conducted: original sprays were applied at 3 different stages of the harvest season (pre-season, early season or mid-season), using either unshaken trees or trees shaken 1 week after spraying. There were no significant (P>0.05) differences among any 3 means (n = 5 trees for ethephon treatments; n = 10 trees for control).

Table 1. Ethephon effects on average nut size and quality during the 2 years following application to unshaken macadamia cv. A16 trees

Different letters indicate significant differences among 3 means (± s.e.) ($P<0.05$, n = 5 trees for ethephon treatments, n = 10 trees for control)

Experiment	Nut-in-shell weight (g)	Kernel weight (g)	Kernel recovery (%)	Kernel oil content (%)
Pre-season spray				
Control	7.39 ± 0.18	3.19 ± 0.06a	43.1 ± 0.4	80.1 ± 0.2
Ethephon (year 1 only)	7.38 ± 0.43	3.15 ± 0.14a	42.6 ± 0.8	80.0 ± 0.3
Ethephon (years 1 & 2)	6.45 ± 0.27	2.81 ± 0.10b	43.9 ± 0.7	80.8 ± 0.4
Early season spray				
Control	8.10 ± 0.24	3.35 ± 0.08	41.3 ± 0.6	80.0 ± 0.1
Ethephon (year 1 only)	7.64 ± 0.52	3.20 ± 0.21	42.5 ± 1.5	80.2 ± 0.2
Ethephon (years 1 & 2)	7.46 ± 0.08	3.28 ± 0.02	44.0 ± 0.3	79.9 ± 0.4
Mid-season spray				
Control	7.97 ± 0.29	3.30 ± 0.09	41.6 ± 0.6	80.2 ± 0.1
Ethephon (year 1 only)	7.12 ± 0.67	3.01 ± 0.21	42.9 ± 1.3	79.6 ± 0.2
Ethephon (years 1 & 2)	7.01 ± 0.47	2.99 ± 0.17	42.7 ± 1.3	80.0 ± 0.2

generally did not affect nut quality in subsequent seasons, but effects on subsequent yield were variable. In 3 of 6 experiments, yield was depressed in the year following first ethephon treatment. However, in 4 of the 6 experiments, 2 consecutive years of ethephon treatment greatly elevated yield in the third year. These ethephon-treated trees consistently provided the highest total yield summed over 2 years, although the effect was not significant ($P>0.05$) in any experiment.

In addition to accelerating cv. A16 fruit abscission, ethephon caused substantial leaf loss, both in the first year of its application (Trueman *et al.* 2002) and when applied in the following year. Young outer leaves were less affected, as found for macadamia cv. 'HAES 333' (Nagao and Sakai 1986) and pecan seedlings (Wood 1985). Ethephon causes leaf loss in other macadamia cultivars (Kadman and Ben-Tal 1983; Gallagher and Stephenson 1985; Trochoulias 1986; Richardson and Dawson 1993) but, for cv. 'Own Choice', Stephenson and Gallagher (1987) found no effect on subsequent yield, even at high ethephon doses (1600 mg/L).

The current study identified a considerable risk of yield decline following ethephon use, at least with a moderate to high dose (1200 mg/L) on cv. A16. It remains unclear why a decline was observed in 3 experiments, rather than all 6, although Trueman *et al.* (2002) noted that the original ethephon treatment in the pre-season experiment on shaken trees was affected by rainfall 1 day after application. Ethephon reduced fruit removal force to a relatively small degree on that occasion, and did not affect yield in the following year. Leaf abscission may have been reduced due to poor ethephon uptake or retention, and subsequent yield may be related to the amount of leaf drop.

Macadamia yield has been correlated with canopy area (Chapman *et al.* 1986; Winks 1986), canopy ground cover (McConchie *et al.* 1999) and hardening vegetative flush during early fruit development (Stephenson *et al.* 1986). Carbohydrate reserves decline during the phase of rapid fruit

Table 2. Ethephon effects on average nut size and quality during the 2 years following application to shaken macadamia cv. A16 trees

Different letters indicate significant differences among 3 means (± s.e.) ($P<0.05$, n = 5 trees for ethephon treatments, n = 10 trees for control)

Experiment	Nut-in-shell weight (g)	Kernel weight (g)	Kernel recovery (%)	Kernel oil content (%)
Pre-season spray				
Control	7.33 ± 0.32	3.04 ± 0.12	41.7 ± 0.4a	79.9 ± 0.1
Ethephon (year 1 only)	7.72 ± 0.32	3.20 ± 0.11	41.4 ± 0.5a	79.6 ± 0.3
Ethephon (years 1 & 2)	7.21 ± 0.11	3.15 ± 0.07	43.8 ± 0.6b	79.5 ± 0.4
Early season spray				
Control	7.95 ± 0.24	3.37 ± 0.09	42.3 ± 0.5	80.2 ± 0.2
Ethephon (year 1 only)	7.80 ± 0.34	3.37 ± 0.14	43.3 ± 0.8	80.1 ± 0.3
Ethephon (years 1 & 2)	7.54 ± 0.36	3.30 ± 0.17	43.7 ± 0.4	80.0 ± 0.5
Mid-season spray				
Control	7.44 ± 0.26	3.19 ± 0.07	43.0 ± 0.6	80.0 ± 0.1
Ethephon (yyear 1 only)	7.54 ± 0.47	3.20 ± 0.18	42.5 ± 0.8	79.6 ± 0.3
Ethephon (years 1 & 2)	7.09 ± 0.21	3.11 ± 0.08	44.0 ± 0.7	79.8 ± 0.2

growth (Stephenson *et al.* 1989*a*, 1989*b*), and fruit set on girdled branches is correlated with available leaf number (Trueman and Turnbull 1994*a*). These results suggest that yield is influenced by carbohydrate availability, sourced perhaps from both stored reserves and current photosynthates. Leaf loss, resulting from ethephon use, probably increased CO_2 assimilation rates of individual remaining leaves (Heichel and Turner 1983; Reich *et al.* 1993; Pinkard and Beadle 1998*a*; Pinkard *et al.* 1998), but may have reduced yields in some experiments by reducing total canopy CO_2 assimilation during the first months after application.

Macadamia trees typically possess a very dense canopy (McConchie *et al.* 1999; Huett *et al.* 2001), and partial defoliation caused by ethephon provided a more open canopy structure. Prolonged, heavy rainfall during flowering was presumed responsible for depressed yield of control trees in the year following the original sprays. The rain was heavy enough to dislodge all sticktight nuts from cv. A16 trees (Trueman *et al.* 2000, 2002), it persisted for several days and appeared to damage flowers, and pollinator bees were inactive. Flower damage appeared particularly severe in the more-open canopies of ethephon-treated trees (S. J. Trueman, pers. obs.). Rain damage should be considered in addition to reduced photosynthetic capacity as a cause of reduced yields in 3 experiments, and rain damage may have been related to the amount of leaf drop. Such heavy rainfall during the macadamia flowering period is uncommon in Australian orchards.

A remarkable result was the substantially higher yield in the third year, obtained in 4 of the 6 experiments, following 2 years of ethephon application (Fig. 2). This was not simply a compensating recovery from poor second-year yield, as third-year yield of trees that were ethephon treated once only did not differ from control tree yield. As macadamia canopies are usually dense, inner leaves or basal canopy leaves can be heavily shaded. Leaf area indices of 14–16, recorded for 11-year-old trees of cv. ‘HAES 344’, are amongst the highest reported for fruit and nut crops (McConchie *et al.* 1999). Across 12 sites of cv. ‘HAES 344’, varying in canopy density from 50 to 95% ground cover, mean photon flux densities in basal shaded positions ranged between 77 and 6% of those in top exposed positions (Huett *et al.* 2001). Macadamia leaves are thick and hypostomatous (Syvertsen *et al.* 1995), with low CO_2 assimilation rates (Lloyd *et al.* 1992) particularly in older shaded leaves (Fletcher *et al.* 2000). Their stomatal conductance in orchard conditions is strongly correlated with both photon irradiance and leaf temperature (Lloyd *et al.* 1991).

Inner-canopy defoliation, resulting from ethephon application, probably improved light penetration and increased CO_2 assimilation of individual remaining leaves, and repeated defoliation may have invoked adaptive responses in canopy architecture and biomass allocation (Heichel and Turner 1983; Reich *et al.* 1993; Pinkard and Beadle 1998*b*; Pinkard *et al.* 1998). Effects on total canopy CO_2 assimilation remain unquantified but, interestingly, significant yield increases only occurred when ethephon had originally been applied pre-season or early season (rather than mid-season). This suggests that 2 successive years of mid-season ethephon treatments might not provide sufficient time for adaptive responses to defoliation, in which case earlier ethephon treatments are likely to be preferable for maximising yield.

Huett *et al.* (2001) also found that, contrary to general trends that nitrogen is allocated preferentially to young leaves, mature hardened leaves of macadamia have higher nitrogen concentrations and nitrogen contents per unit leaf area. Older macadamia leaves can be significant sinks for xylem-fed ^{15}N, especially on non-flushing branches (Fletcher *et al.* 2000). Inner-canopy defoliation may have removed competing sinks for nitrogen, and possibly other nutrients, elevating nutrient levels in productive outer leaves. In addition, many leaves of ethephon-treated trees became chlorotic before abscission, suggesting that significant nutrient translocation occurred from older leaves following ethephon use. Most leaf abscission occurred between 2 and 4 weeks after treatment. Abscised leaves were left near, but not directly under, treated trees during harvesting. Re-uptake of nutrients from the decomposing leaves cannot be discounted, and re-uptake by experimental trees could have been greater had blocks of trees rather than individual trees been ethephon treated.

Ethephon application may also have altered vegetative flushing patterns, soil water use, or pollinator accessibility to macadamia trees. Vegetative growth of macadamia occurs at any time of year, but often with peaks in spring and in late summer–autumn (Cormack and Bate 1976; Stephenson *et al.* 1986; Stephenson and Gallagher 1989; Nagao *et al.* 1994). Yields have been related to flush phenology in macadamia (Stephenson *et al.* 1986), and 2 years of inner-canopy defoliation by ethephon may have increased yields by affecting timing or extent of vegetative growth. Inner-canopy defoliation would also have affected total canopy transpiration, and possibly also root flushing, potentially maintaining higher soil water potential during dry periods. However, the site was watered from a very large irrigation supply, and macadamia trees appear highly tolerant of soil water deficits (Lloyd *et al.* 1991) and show little or no response to irrigation in higher rainfall regions (Trochoulias and Johns 1992).

Both major pollinators of macadamia in Australia, *Apis mellifera* and *Trigona carbonaria*, were present at the experimental site, and both usually prefer to forage on outer racemes rather than inner, shaded racemes (Heard and Exley 1994). Flowering was not quantified in this study, but it did not appear to be severely affected by ethephon treatments. Fruit set can be increased by extra cross-pollination

(Trueman and Turnbull 1994*b*; Wallace *et al.* 1996), and so inner canopy defoliation may have increased third-year yield by improving pollinator visitation to flowers. In the year that ethephon treatment did not increase yields, pollinator visitation had been very poor due to heavy rainfall.

NIS and kernel sizes were higher in the year with low yield but usually did not differ between treatments, either in the year of the original spray (Trueman *et al.* 2002) or in the subsequent 2 years. Reduced kernel size in 1 experiment (Table 1) contrasted with increased kernel recovery in another (Table 2), but these were 2 isolated examples among 16 cases in which ethephon had no effect on size or kernel recovery. A very high percentage of Grade 1 kernels is typical for cv. A16 (e.g. Gallagher *et al.* 1999), and kernel oil contents were consistently well above the 72% requirement for Grade 1 kernels. These results confirm that early harvest of cv. A16 is feasible in Australian orchards, where flowering is typically brief and highly seasonal (Moncur *et al.* 1985; Stephenson and Trochoulias 1994; Meyers *et al.* 1995; Gallagher 1996) and where kernel oil accumulates several months before natural abscission (Trueman *et al.* 2000).

Ethephon application before tree shaking is the most effective means of harvest acceleration in macadamia, with almost-complete crop removal in cv. A16 if used at the start of natural abscission (Trueman *et al.* 2002). Similar approaches have been used in olive (Ben-Tal and Wodner 1994; Denney and Martin 1994; Tous *et al.* 1995) and tested on crops such as pecan (Stein *et al.* 1987; Wood 1989) and orange (Kender *et al.* 2001). Ethephon causes abscission of elongating macadamia racemes and should not be used once racemes become visible (Kadman and Ben-Tal 1983; Stephenson and Gallagher 1987; Richardson and Dawson 1993). At the study site, this occurred about 2 months after commencement of natural abscission (e.g. 27 July 1998, 17 July 2000), providing ample treatment opportunity.

The risks and benefits of inner-canopy defoliation by ethephon warrant further investigation, particularly given the considerable yield gains after 2 years of ethephon-assisted harvest. Removal of live branches in the lower canopy ('green pruning') has become an important technique for improving wood quality in some eucalypt plantations. Removal of the lower 50% of canopy length, at *Eucalyptus nitens* canopy closure, increases light-saturated CO_2 assimilation rates and leads to adaptive changes in leaf morphology, leaf area and foliage distribution (Pinkard and Beadle 1998*b*; Pinkard *et al.* 1998, 1999). Daily net biomass production (G_d) is depressed for several months following pruning, but cumulative G_d exceeds that of unpruned trees over a 20-month period. Leaf area indices in these eucalypt plantations (about 6 before pruning; Pinkard *et al.* 1999) are likely to be lower than those of mature macadamia orchards (McConchie *et al.* 1999). Photosynthetic responses to ethephon application await determination, but inner-canopy defoliation may represent a powerful technique for canopy management of trees with very dense canopies, such as macadamia.

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