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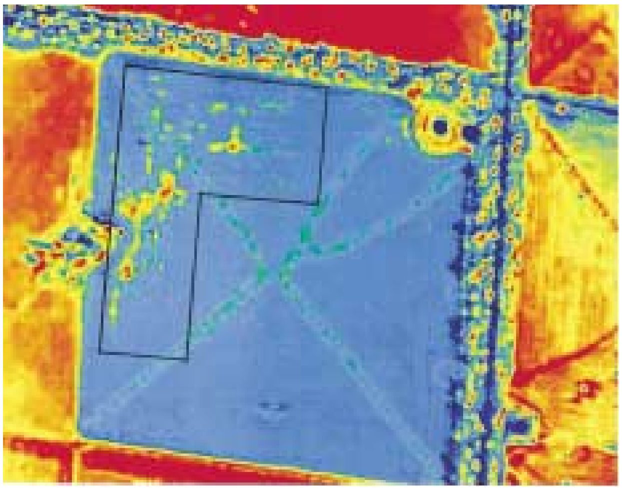

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Ethephon promotion of crop abscission for unshaken and mechanically shaken macadamia

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Abstract. Promotion of fruit abscission in macadamia, *Macadamia integrifolia* (Proteaceae), has potential to reduce costs associated with prolonged harvesting of late-abscising cultivars. Effects of ethephon [(2-chloroethyl)phosphonic acid] on fruit removal force and crop abscission were monitored at 3 stages of the harvest season on both unshaken and mechanically shaken trees of the late-abscising macadamia cultivar A16. Ethephon application, tree shaking, or a combination of the 2 methods, accelerated crop removal from the tree at all stages during harvest. Early harvest before natural abscission resulted in little or no difference in nut-in-shell and kernel weight, kernel recovery and kernel oil content. Delaying ethephon application or tree shaking until commencement of natural abscission resulted in greater crop removal. Fruit removal force declined naturally towards 1 kgf at this stage, and was further reduced by ethephon application. The most effective approach for harvest acceleration was to reduce fruit removal force, before tree shaking, by spraying trees with ethephon.

Introduction

Macadamia fruits are usually harvested by mechanical sweeping of the orchard floor following natural fruit abscission. Maximum intervals of 4 weeks between sweeps have been recommended to avoid nut deterioration, although longer intervals may be satisfactory during dry weather (Mason and Wells 1984; Nagao and Hirae 1992; Liang *et al.* 1996). Most orchards contain more than 1 cultivar to maximise cross-pollination (Ito and Hamilton 1980; Trueman and Turnbull 1994; Wallace *et al.* 1996), but cultivars differ in timing of abscission and some have very extended abscission periods. Consequently, harvesting generally continues over several months, involving multiple sweeps of the same rows. Promotion of abscission has potential to lower costs associated with prolonged harvesting and reduce environmental impacts associated with soil disturbance.

Accelerated macadamia abscission has been accomplished using the ethylene-generating compound, ethephon [(2-chloroethyl)phosphonic acid] (Nagao and Hirae 1992). Ethephon sprays reduce harvest duration, although the technique is not widely practiced in some countries due to variable results and possible effects on future yield. Effectiveness of ethephon may be influenced by timing of application within the harvest season (Trochoulias 1986; Nagao and Sakai 1988; Richardson and Dawson 1993), addition of wetting agent to the solution (Gallagher and Stephenson 1985; Richardson and Dawson 1993) and neutralisation of the ethephon solution to accelerate ethylene release (Kadman and Ben-Tal 1983). Mechanical tree shaking has also been used, particularly in Hawaii, to induce macadamia nut drop (Gillespie *et al.* 1975; Nagao and Hirae 1992).

A major focus for abscission promotion in Australian orchards includes cultivars exhibiting late-season abscission, such as ‘Hidden Valley A16’ (A16) and ‘HAES 246’. Kernel oil accumulation in these cultivars is completed several months before abscission, but fruit removal force declines very slowly and fruits remain on the tree up to several months after harvest of other cultivars (Trueman *et al.* 2000). This study investigated methods to accelerate abscission in cv. A16. Experiments were conducted on unshaken trees and on trees that were mechanically shaken after spray application. The effects of ethephon, solution pH and solution additives on fruit removal force and crop abscission were assessed, and nut size and quality were monitored throughout the harvest season.

Materials and methods

Plant material

Trees of cv. A16, about 7 years old, were selected in a commercial orchard at Winfield, Queensland, Australia (24°32′S, 152°01′E). Alternate trees were selected to avoid spray drift onto other experimental trees. The experiments were conducted in a pure cv. A16

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block, at least 7 rows from a mixed cvv. 'HAES 344' and 'HAES 741' block, and at least 9 rows from a pure cv. 'Hidden Valley A4' block. Trees were about 5 m high, and had received little pruning except for removal of branches within 1 m of the ground.

Experimental design and treatments

Experimental treatments were applied at 3 stages of fruit abscission: before abscission had commenced ('pre-season'), at the commencement of abscission ('early-season') and during abscission ('mid-season'). Two experiments were performed at each stage, 1 utilising unshaken trees and the other utilising trees to be mechanically shaken. Forty trees were used for each of the 6 experiments (i.e. treatment dates), consisting of 8 trees in each of 5 rows. Each row was regarded as a block. The 6 experiments were analysed separately as some different rows had to be used for each experiment, and treatments on the unshaken and shaken trees were applied on different dates.

Treatments were allocated randomly in a 2 by 2 by 2 factorial combination to the 8 trees in each row. Treatments consisted of spraying the whole tree with a solution of ethephon at either 0 or 1200 mg/L, prepared from Ethrel (Rhône-Poulenc) in deionised water. Either wetting agent [0.05% v/v Agral 600 (i.e. nonylphenolpolyglycol ether)] (ICI) (Trochoulias 1986; Richardson and Dawson 1993) or drying retardant (1% v/v glycerol) (Ben-Tal 1987; Banno *et al.* 1993) was added to the solution, at either pH 2.0 (the unadjusted pH of the ethephon solution at 1200 mg/L) or pH 7.0. Adjustments to pH were made using hydrochloric acid or sodium hydroxide. All solutions were prepared immediately before spraying. Trees were sprayed to run-off, which required about 4.5 L per tree.

Sprays on unshaken trees were applied on 24 March, 12 May or 8 July 1998 for the pre-season, early season or mid-season experiments, respectively. Sprays on trees to be mechanically shaken were applied on 16 April, 4 June or 16 July 1998 for the same respective experiments. All sprays were applied between 0900 and 1500 hours on fine days, but rainfall did occur on the day following the spray application on 16 April 1998. Tree shaking was performed 1 week after spraying, applying an about 5 s shake through the trunk using a tractor-mounted EnviroHarvester tree shaker (Graham Grove Enterprises, Lismore, NSW). Floral buds of the following season were not visible macroscopically until 27 July 1998.

Data collection and analysis

Fruit were harvested from the ground immediately before spraying and at 1, 2 and 4 weeks after spraying. An additional harvest was performed 3 weeks after spraying for the experiments on unshaken trees. The removal forces of 10 fruit per tree, when available, were determined on the same days using a linear force meter (Shimpo Instruments, Lincolnwood, Illinois) with attached aluminium collar, and the fruit were retained. On the days that trees were shaken, removal forces were determined before shaking. Other harvests were performed before or after this 4-week period, as required, to obtain complete yield and cumulative abscission records for each tree. Crop removal was taken as cumulative fruit abscission 4 weeks after spray application, unless otherwise stated.

All fruit were dehusked using a commercial dehusker that excluded non-commercial small nuts (<19 mm diameter), and nuts were then dried in fan-forced laboratory ovens at 45°C for 6 days. Nuts carried over from previous seasons (i.e. sticktights) and other unsound nuts (e.g. pest- or disease-affected nuts) were removed and excluded from the analyses. Total nut-in-shell (NIS) weights were recorded for all samples, total tree yields were calculated, and cumulative crop abscission (weight of abscised NIS as a percentage of total tree yield) was determined at each time point for each tree. Efficiency of mechanical tree shaking was also determined for each shaken tree. Shaker efficiency was expressed as the fruit that dropped during shaking, as a percentage of fruit in the tree before shaking.

For all trees sprayed with solutions containing Agral 600 (i.e. 1 half of the experimental trees), 5 nuts from each harvest were cracked and weighed to determine average NIS weight, kernel weight and kernel recovery. The oil content of each kernel was then determined from its specific gravity measured using a pan immersed in a 95% (v/v) ethanol solution (McConchie *et al.* 1996; Meyers *et al.* 1999; Trueman *et al.* 2000), with the following formula:

$$\text{Oil content (\%)} = 284.7 - 212.57 \times \text{specific gravity},$$

where specific gravity = (0.7995 × air weight)/(air weight – weight in 95% ethanol).

Statistical analyses of nut size and quality were performed for each harvest. In addition, average nut size and quality across all harvests were calculated for each tree (weighted according to the NIS yield of each harvest), to assess the impact of experimental treatments on overall size and quality.

Fruit removal force and abscission results were assessed using factorial analyses of variance, with rows regarded as blocks, and pre-spray values for removal force and fruit abscission for each tree considered as covariates. Shaker efficiency, nut size and quality results were analysed using factorial analyses of variance regarding rows as blocks, but without covariates. A relationship was derived between fruit removal force and natural fruit abscission, using all the samples from unshaken trees receiving no ethephon, as well as pre-ethephon or pre-shaking samples from the other trees. Means are reported with standard errors.

Results

The NIS yield of experimental trees was 8.54 ± 0.10 kg (n = 240). No fruit remained in the trees at the final harvest (i.e. no sticktights), possibly due to heavy rainfall in early September. The type of additive used in the treatment solution (Agral or glycerol) and solution pH (2.0 or 7.0) had no significant effect on fruit removal force, crop removal or shaker efficiency, except that fruit removal force following sprays of pH 2.0 was slightly less than following sprays of pH 7.0 at 2 weeks post-spray in the pre-season experiment on shaken trees (1.42 ± 0.07 *v.* 1.57 ± 0.07 kgf; $P<0.01$). Further comparisons of removal force, crop removal and shaker efficiency were made only between pooled data from all 0 or 1200 mg/L ethephon treatments.

Fruit removal force

Fruit removal force declined steadily throughout the season on trees receiving no ethephon, from about 1.7 kgf initially for the pre-season experiments to about 1.1 kgf at the conclusion of the mid-season experiments (Fig. 1). Ethephon treatment reduced fruit removal force within 1 week of application, and mean removal forces remained lower than controls throughout each experiment ($P<0.05$). Ethephon reduced mean removal forces by about half in all experiments, except for the pre-season experiment on shaken trees which may have been affected by rainfall 1 day after spraying. Fruit abscission occurred naturally when mean removal force approached 1 kgf, at which point about 50% of fruit had fallen (Fig. 2).

Fruit abscission — unshaken trees

Fruit abscission for trees receiving no ethephon commenced in late May and continued through to early September (Fig. 3*a–c*). Ethephon treatment increased fruit abscission within 2 weeks of spraying at all stages ($P<0.001$), but crop removal was much greater following early season and mid-season applications. Crop removal was 33, 81 and 96% at 4 weeks after the pre-, early- and mid-season ethephon sprays, respectively (compared with 0.4, 11 and 62%, respectively, for controls). Increased abscission following ethephon application was maintained to the 11 August 1998 harvest in all 3 experiments ($P<0.001$).

Fruit abscission — shaken trees

Ethephon application increased crop removal by tree shaking at all 3 stages of the season ($P<0.001$) (Fig. 3*d–f*).

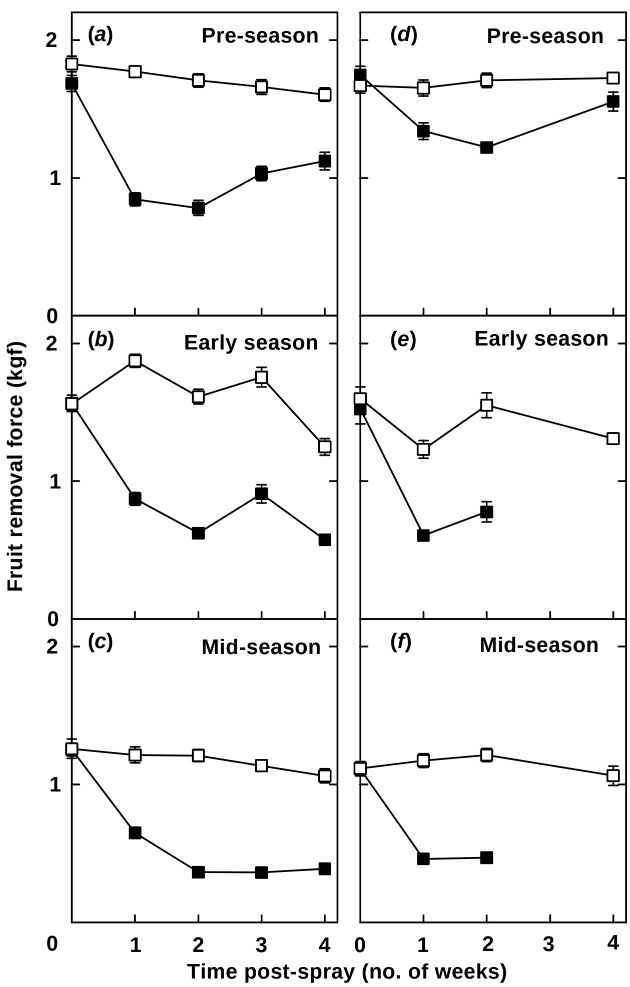

Figure 1. Removal forces of macadamia cv. A16 fruit sampled up to 4 weeks after spraying without ethephon (□) or with ethephon at 1200 mg/L (■) at 3 different stages of the harvest season. (*a–c*) Unshaken trees, sprayed 24 March (pre-season), 12 May (early season) or 8 July (mid-season); (*d–f*) trees shaken 1 week after spraying on 16 April (pre-season), 4 June (early season) or 16 July (mid-season). Means ± s.e. ($n = 20$ trees).

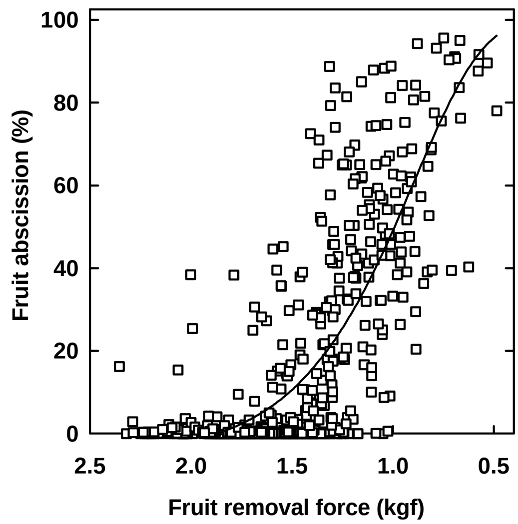

Figure 2. Relationship between fruit removal force and natural fruit abscission for macadamia cv. A16.

$$\text{Fruit abscission (\%)} = 100 - (105.83 \times e^{\{-e^{[-(\text{fruit removal force} - 0.89)/0.34]}\}}),$$

where fruit removal force is expressed in kgf ($r^2 = 0.62$, $P<0.0001$).

Crop removal immediately after tree shaking was 56, 92 and 97% following the pre-, early- and mid-season ethephon sprays, respectively, significantly greater in each case than the controls (40, 75 and 86%). Shaker efficiency was also increased by ethephon application (Table 1). Shaker efficiencies were much higher after commencement of natural abscission than in the pre-season.

Cumulative abscission 4 weeks after ethephon application was 64, 98 and 99%, pre-, early- and mid-season, respectively (compared with 41, 80 and 89%, respectively, for controls). Increased abscission following ethephon application was maintained to the 11 August 1998 harvest in all 3 experiments ($P<0.001$).

Table 1. Ethephon effects on shaker efficiency for macadamia cv. A16 trees

Shaker efficiency is expressed as the fruit that dropped during shaking, as a percentage of fruit in tree before shaking
Significant differences between two means (± s.e.) are indicated by different letters ($P = 0.001$, $n = 20$ trees)

Experiment	Shaker efficiency (%)
Pre-season spray	
Control	39.1 ± 2.2a
Ethephon	55.5 ± 2.3b
Early season spray	
Control	70.1 ± 3.6a
Ethephon	89.4 ± 1.4b
Mid-season spray	
Control	71.6 ± 2.5a
Ethephon	93.4 ± 0.6b

Table 2. Ethephon effects on average nut size and quality (across all harvests) of unshaken macadamia cv. A16 trees

Significant differences between two means (± s.e.) are indicated by different letters ($P = 0.05$, $n = 10$ trees)

Experiment	Nut-in-shell weight (g)	Kernel weight (g)	Kernel recovery (%)	Kernel oil content (%)
Pre-season spray				
Control	6.89 ± 0.12	3.06 ± 0.07	44.2 ± 0.4	79.6 ± 0.2
Ethephon	6.80 ± 0.09	3.01 ± 0.04	44.1 ± 0.4	79.9 ± 0.2
Early season spray				
Control	6.87 ± 0.14	2.98 ± 0.05	43.3 ± 0.3a	79.3 ± 0.1
Ethephon	6.95 ± 0.12	3.09 ± 0.06	44.2 ± 0.3b	79.6 ± 0.2
Mid-season spray				
Control	6.97 ± 0.11	3.06 ± 0.05	43.8 ± 0.3	79.5 ± 0.1
Ethephon	6.76 ± 0.13	3.03 ± 0.06	44.7 ± 0.5	79.8 ± 0.2

Table 3. Ethephon effects on average nut size and quality (across all harvests) of shaker-harvested macadamia cv. A16 trees

Significant differences between two means (± s.e.) are indicated by different letters ($P = 0.05$, $n = 10$ trees)

Experiment	Nut-in-shell weight (g)	Kernel weight (g)	Kernel recovery (%)	Kernel oil content (%)
Pre-season spray				
Control	6.77 ± 0.17	3.04 ± 0.07	44.8 ± 0.3a	79.9 ± 0.1
Ethephon	6.75 ± 0.15	2.96 ± 0.07	43.6 ± 0.2b	79.6 ± 0.2
Early season spray				
Control	7.32 ± 0.14	3.22 ± 0.05a	43.9 ± 0.4	80.1 ± 0.2
Ethephon	6.83 ± 0.14	2.97 ± 0.06b	43.2 ± 0.4	79.5 ± 0.3
Mid-season spray				
Control	6.82 ± 0.18	3.08 ± 0.09	45.0 ± 0.4a	79.8 ± 0.1
Ethephon	6.80 ± 0.12	3.01 ± 0.07	44.0 ± 0.4b	79.6 ± 0.2

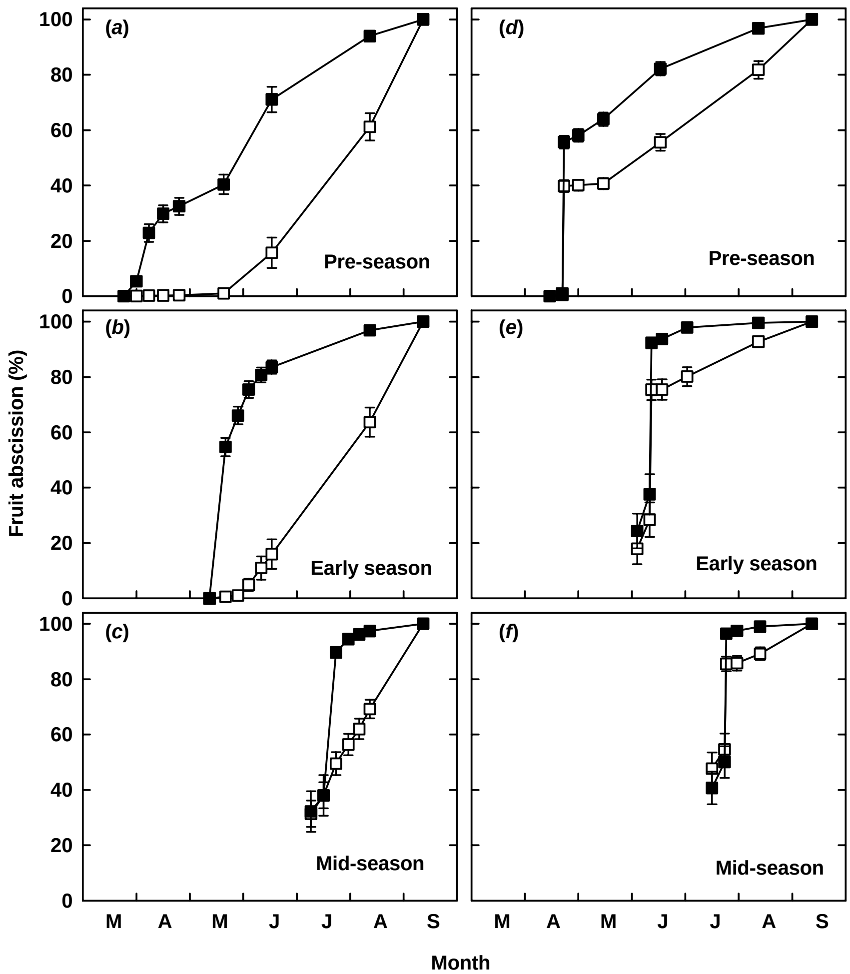

Figure 3. Abscission of macadamia cv. A16 fruit after spraying without ethephon (□) or with ethephon at 1200 mg/L (■) at 3 different stages of the harvest season. The first point on each graph indicates the time of spraying. (*a–c*) Unshaken trees, sprayed 24 March (pre-season), 12 May (early season) or 8 July (mid-season); (*d–f*) trees shaken 1 week after spraying on 16 April (pre-season), 4 June (early season) or 16 July (mid-season). Means ± s.e. ($n = 20$ trees).

Nut size and quality

On almost all sampling dates, neither ethephon application nor solution pH significantly affected NIS weight, kernel weight or kernel recovery (data not shown). Ethephon application had also little or no effect on kernel oil content of fruit sampled from the ground (Fig. 4) or from the tree (data not shown; means were very similar to those from the ground). Solution pH only had a significant effect on kernel oil content for fruit removed by shaking in the early season experiment (79.8 ± 0.2%, pH 2.0 *v.* 80.4 ± 0.2%, pH 7.0) ($P<0.05$). Mean oil contents from all experiments, including those involving pre-season harvests, were all above 78%, exceeding the 72% oil content required for 'Grade 1' industry-standard kernels.

Ethephon application had little or no effect on average nut size and quality for each tree (i.e. the combined average of all harvests), both for unshaken trees (Table 2) and shaken trees (Table 3). No significant effects of solution pH on average nut quality were detected.

Discussion

Accelerated abscission of mature macadamia cv. A16 fruit was accomplished using ethephon application, mechanical tree shaking, or a combination of the 2 methods, but effectiveness of these methods depended on the time of treatment. Natural abscission of cv. A16 fruit commenced in late May and continued until early September, significantly later than for other widely planted cultivars such as 'HAES 344' and 'HAES 741' (Trueman *et al.* 2000), grown in the same orchard. Ethephon treatment or tree shaking before natural abscission removed a significant percentage of the crop within 4 weeks, but crop removal was much greater with treatment at the commencement of natural abscission.

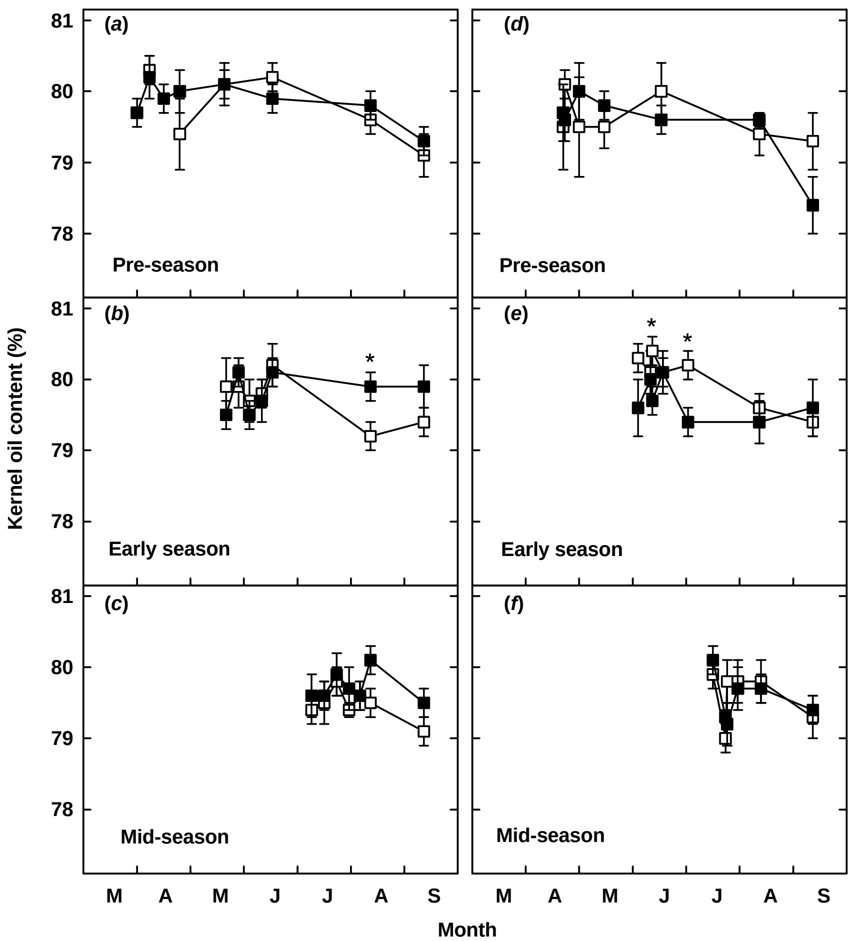

Figure 4. Kernel oil content of macadamia cv. A16 fruits harvested from the ground after spraying without ethephon (□) or with ethephon at 1200 mg/L (■) at 3 different stages of the harvest season. The first point on each graph indicates the time of spraying. (*a–c*) Unshaken trees, sprayed 24 March (pre-season), 12 May (early season) or 8 July (mid-season); (*d–f*) trees shaken 1 week after spraying on 16 April (pre-season), 4 June (early season) or 16 July (mid-season). Means ± s.e. (n = 10 trees). Asterisks indicate significant differences between 2 means ($P < 0.05$).

Greater response to ethephon at commencement of natural abscission may indicate that sensitivity to ethylene increased at this stage. Increases in sensitivity to ethephon throughout the harvest period have been reported for cvv. 'Own Choice', 'HAES 333' and 'Beaumont' (Trochoulias 1986; Nagao and Sakai 1988; Richardson and Dawson 1993). However, natural fruit abscission is also associated with declining removal force (Sakai and Nagao 1984; Trueman *et al.* 2000), occurring as the mean removal force approached 1 kgf in cv. A16. Delaying ethephon application or tree shaking until commencement of natural abscission ensured that most fruit had already attained low removal force. For example, removal force was less than 1.5 kgf for 52 and 59% of fruit at the commencement of the 2 early season experiments (12 May 1998 and 4 June 1998, respectively) (data not shown). Studies of ethylene evolution *in vitro* indicate that increased ethylene production precedes the abscission period of immature macadamia fruit (Sakai and Nagao 1984). Removal force decline and abscission may be preceded by increased ethylene production and/or ethylene sensitivity, but this hypothesis remains untested for mature macadamia fruit.

Spray coverage may be important for treatment efficiency, as absorption through the pedicel is an important component of ethephon uptake in crops such as olive (Banno *et al.* 1993; Denney and Martin 1994). Wetting agents incorporated in ethephon solutions have been previously tested on macadamia (Kadman and Ben-Tal 1983; Gallagher and Stephenson 1985; Trochoulias 1986; Stephenson and Gallagher 1987; Nagao and Sakai 1988; Richardson and Dawson 1993). Addition of the drying retardant, glycerol, had not been tested on macadamia, but had been used on olive to increase ethylene evolution, further reduce removal force (Ben-Tal 1987) and increase fruit abscission (Banno *et al.* 1993). Results for cv. A16, at 1200 mg/L ethephon, indicated no benefit from use of a drying retardant instead of a standard wetting agent.

Abscission rates for cv. A16 were unaffected by neutralisation of the spray solution (i.e. from pH 2.0 to pH 7.0). Ethephon is stable below pH 4 but decomposes to ethylene gas at higher pH such as in plant cell cytoplasm (Gianfagna 1995). Neutralisation of the ethephon solution, to achieve a more rapid release of ethylene, greatly increased cv. 'Beaumont' fruit abscission when ethephon at 500 mg/L was used in Israel, but did not affect abscission at 1000 and 1500 mg/L (Kadman and Ben-Tal 1983). Neutralisation did not affect abscission at 200 or 400 mg/L on the same cultivar in New Zealand (Richardson and Dawson 1993).

Leaf abscission following ethephon application to cv. A16, although not quantified, was substantial. Leaves were shed primarily from inside the canopy, with young outer leaves less affected. Leaf loss was reported by Kadman and Ben-Tal (1983), Gallagher and Stephenson (1985), Trochoulias (1986) and Richardson and Dawson (1993). Leaf drop was considered not excessive by Gallagher and Stephenson (1985), who reported no ethephon effects on following yield of cv. 'Own Choice', even with 1600 mg/L ethephon (Stephenson and Gallagher 1987). Ethephon effects on yield and nut quality over subsequent years have been monitored following all 6 experiments of the current study, and will be reported in a following paper.

Mechanical tree shaking is another option for accelerating the macadamia harvest, without causing leaf abscission. Statistical comparisons between experiments using unshaken and shaken trees are not valid because of different spray dates and the use of different orchard rows. However, at all stages of the season, the amount of cv. A16 crop removed by tree shaking was similar to the amount removed using an ethephon spray at 1200 mg/L. The most effective means of crop removal was to reduce fruit removal force, before tree shaking, by spraying trees with ethephon. This approach, used after commencement of natural abscission, removed about 90% of remaining fruit during the 5-s shaking process alone (Table 1). Therefore, considerable potential exists for harvest in nets or other collection devices during mechanical shaking of macadamia trees.

Early harvest of cv. A16 did not reduce nut quality. Little or no difference in kernel oil content was apparent between ethephon-treated and untreated trees, between shaken and unshaken experiments, from pre-season to mid-season treatments, or across sample dates within experiments. Flowering in Australian orchards is typically brief and strongly seasonal (Moncur *et al.* 1985; Stephenson and Trochoulias 1994; Meyers *et al.* 1995; Gallagher 1996), in contrast with the extended flowering of other production areas such as Hawaii (Nagao and Sakai 1990; Nagao and Hirae 1992; Nagao *et al.* 1994). Kernel oil content may be affected by extreme temperatures during the oil accumulation phase (Stephenson and Gallagher 1986), but results for cv. A16 (McConchie *et al.* 1996; Trueman *et al.* 2000) and cvv. 'HAES 508' and 'H2' (Baigent 1983) indicate little or no seasonal differences in the timing of maximal oil accumulation in Australian orchards. The current results confirm that kernel oil accumulation is generally completed before fruit abscission (Jones 1937, 1939; Liang and Myers 1975; Baigent 1983; McConchie *et al.* 1996), and by several months before abscission of late cultivars such as A16 and 'HAES 246' in Australia (Trueman *et al.* 2000).

Because oil accumulation is completed before natural abscission, accelerated harvest of macadamia appears feasible as with other nut crops such as pistachio, pecan, and almond (e.g. Crane 1978; Herrera 1994; Gurusinghe and Shackel 1995). A combination of ethephon application and tree shaking, commonly used for olive harvesting (Ben-Tal and Wodner 1994; Denney and Martin 1994; Tous *et al.* 1995), is likely to be the most effective approach for macadamia. However, the appropriate method for each orchard will ultimately depend on several factors, including the relative costs of ethephon application and tree shaking, effects on following yield and quality, the number of trees requiring earlier harvest, and the preferred supply times of macadamia processors.

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