Effects of Early Tree Training on Macadamia Production

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SUMMARY. The current industry recommendation for the training of young macadamia (Macadamia integrifolia, Macadamia tetraphylla, and hybrids) trees is to prune the trees to a central leader, but there is little science to support this recommendation. We planted an orchard to assess the merits of central leader training relative to a minimally pruned control. We used two cultivars, 246 and 816, representing spreading and upright growth habits, respectively. Training to a central leader reduced cumulative yields per tree over the first 3 years of production by 16% in ‘246’ and 23% in ‘816’. The reduction in yield was correlated with a reduction in the number of racemes per tree. The early training of the upright cultivar 816 appeared to improve its resistance to storm damage, but no such effect was seen in the more spreading cultivar 246. The yield penalty in training young trees to a central leader is such that industry should reconsider its early tree training recommendation.

Macadamia trees have a tendency to develop multiple leaders with narrow branch angles, and are prone to splitting in high wind. To reduce the risk of wind damage, the recommendation in Australia, South Africa, and Hawaii has been to train trees early to a central leader that supports whorls of widely angled scaffold limbs (Alan, 1975; Nagao, 1983; O’Hare et al., 2004; Storey et al., 1953). In Australia, the recommendation has not been widely adopted, possibly due to the high cost of manual pruning; mature trees with multiple leaders and narrow branch angles are common.

More recently, there has been speculation that central leader training combined with ongoing selective limb removal as the tree matures, may maintain better canopy light penetration and productivity (Bekker, 2008; Horticulture Australia Limited, 2001, 2003; Huett, 2004; McFadyen et al., 2004a; Shaw, 2006; van Niekerk, 2008; Wilson et al., 2010) and control tree size relative to nonpruned trees (McFadyen et al., 2004a; Wilson et al., 2010). However, the little work that has been done in these areas is not particularly supportive.

Trocoulias (1983) trained ‘246’ trees to a central leader, starting 6 months after planting, with follow-up pruning every 4 to 8 weeks for the next 2 years. In total, the trees were pruned on 14 occasions. The cumulative yield of the trained trees in the 4th and 5th years after planting was 73% lower than that of the nonpruned control trees. The large yield penalty was likely related to the high frequency of pruning. The published guides to training trees to a central leader only suggest pruning the trees every 3 to 6 months in the first 2 years after planting (Nagao, 1983; Storey et al., 1953).

Olesen et al. (2011) reported that pruning 6-year-old ‘849’ trees to a central leader reduced yield relative to nonpruned trees by 14% over 4 years, but, as the authors suggested, the yield penalty may have been less if the pruning had been undertaken earlier.

Our aim was to compare the industry recommendation for early tree training with a minimally pruned control that is more representative of current industry practice. A workshop was conducted before treatment application with industry members to decide on the specifics of the two treatments. The trial was planted in Mar. 2007, using cultivars 246 and 816, these being representative of spreading and upright cultivars, respectively (Vock and Bell, 1998). Data on tree dimensions from 2008 to 2013, flowering in 2010 and 2011, and yields from 2011 to 2013 are presented here.

Materials and methods

The two cultivars used in the trial, 246 and 816, are believed to be M. integrifolia (Peace et al., 2004). The trees were grafted onto seedling rootstocks grown from fruit from ‘H2’ trees [M. integrifolia (Peace et al., 2002)] and planted in Mar. 2007 in north–south rows at 7 × 3.9 m at the Center for Tropical Horticulture, Alstonville, New South Wales, Australia (lat. 28.9°S, long. 153.5°E). Two treatments were applied to each cultivar: training to a central leader and a minimally pruned control.

All trees were pruned back to a single stem in June 2007. The remaining stem on each tree was then topped at three or four nodes above the rootstock. The control trees were not pruned again. The trained trees were pruned by largely following the guidelines described by O’Hare et al. (2004) with the following variations. After topping, buds in two of the three axils in the uppermost whorl on the stem were removed. The intention was that the remaining bud would form the central leader without

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| Units | To convert U.S. to SI, multiply by | U.S. unit | SI unit | To convert SI to U.S., multiply by |
|-------|-------------------------------|----------|--------|-------------------------------|
| 0.3048 | ft | m | 3.208 | 0.3937 |
| 2.54 | inch(es) | cm | 0.0394 |
| 25.4 | inch(es) | mm | 0.3937 |
| 0.4536 | lb | kg | 2.2046 |
| 28.3495 | oz | g | 0.0353 |
competition from other shoots at that node and that shoots from the node below would form the first layer of scaffold branches. However, in Aug. 2007, we observed that the shoot from the uppermost whorl on around 30% of the pruned trees had been lost or was stunted whereas shoots from the node below had grown more vigorously. Given this, the trees were topped to 10 to 15 mm above the second node and a central leader and scaffold branches were selected from the shoots at that node. At subsequent prunings, if no branches had formed on the central leader within ≈60 cm of the last layer of scaffold branches, the leader was tipped to promote branching. Dense whorls of branches that had developed on scaffold branches close to the trunk were thinned to outside branches to encourage horizontal growth. Long unbranched scaffolds were tipped to promote branching and development of flowering wood. After Aug. 2007, trees were pruned in Nov. 2007, Mar. 2008, Sept. 2008, and Apr. 2009. At the final pruning, the uppermost node of the central leader of many trees could no longer be reached from the ground. The fresh weights of prunings were measured at each pruning time except at the remediation pruning in Aug. 2007.

The four treatments (two cultivars × two training systems) were arranged in a randomized complete block design, with five blocks, one plot of each treatment per block, and each plot comprising four × four trees. Measurements of yield, fruit quality, pruning weight, and raceme number were made on the fully buffered central four trees of each plot, except for the ‘246’ control trees where measurements were taken from only three of the four trees for yield, fruit quality, and raceme number in three of the five plots owing to storm damage to the fourth tree.

During the course of the experiment, it appeared that more nuts were produced on buffer trees in the control plots immediately adjacent to the control plots of the other cultivar suggesting a pollen parent effect. We tested this idea by making additional yield measurements in 2012 and 2013 for these buffer trees. Such juxtapositions occurred in four of the five blocks. The trees at the ends of rows were not included in these yield measurements, so that either three or four trees were harvested in each plot.

Tree height was measured in July– Sept. from 2008 to 2013 and canopy width, at the widest part of the tree, was measured in Jan. 2009 and in June–July from 2009 to 2012. Flower racemes were counted around anthesis in 2010 and 2011. Fruit were harvested from the trees in Apr. 2011, and from the ground in 2012 and 2013, at about monthly intervals from April until September.

Fruit were dehusked and total “nut-in-shell” (NIS) weight per plot was recorded. A subsample of 100 NIS was taken from each plot to estimate moisture content and average NIS weight. The subsample moisture content was used to express the whole plot NIS weight and average NIS weight at 10% moisture content, which was the industry standard until very recently, when it was changed to 3%.

In 2013, the fruit were further assessed for kernel recovery, unsound kernel, and first-grade kernel. Kernel recovery is the kernel weight expressed as a percentage of the total NIS weight. Unsound kernel is kernel affected by insect damage, mould or decay, or characterized by immaturity, discoloration, germination, or rancidity (Australian Macadamia Society, 1995) and is expressed relative to the NIS on a percentage weight-by-weight basis. First-grade kernel is sound kernel with an oil content of 72% or more, based on whether it floats in tap water (Mason and Wills, 1983) and is expressed relative to the total sound kernel weight on a percentage weight-by-weight basis.

All the trees in the trial, including all the buffer trees, were assessed for storm damage on 25 May 2009 and on 29 Jan. 2013, each time shortly after a severe storm.

Statistical analyses were conducted in the R environment (R Core Team, 2015) including tools from the ASReml-R package (Butler et al., 2009). Linear mixed models were used to explain trait variability, according to fixed effects of cultivar, pruning, season, and their interactions. Spatial variability in the orchard was estimated by random effects associated with the rows and columns of the plots. Potential in-trait correlation was accommodated by inclusion of random plot effects. The variation in the numbers of racemes increased as the numbers increased, so the numbers were modeled on the natural logarithm scale to meet the assumption of independently distributed errors. Null hypothesis significance tests for the fixed effects were conducted by calculation of F statistics. The models were used to estimate means and standard errors for each trait, for each cultivar, pruning practice, and season. Estimates of least significant difference at 5% critical value were also calculated to enable statistical inference for specific effects. Pruning weights were analyzed by two-way analysis of variance or t tests. Storm damage, representing the number of trees either lodged or snapped, was analyzed using the G test with the Williams’s correction (Sokal and Rohlf, 1995). Logistic curves were fitted to the means in Fig. 1 by nonlinear regression analyses, as visual aids to help with the interpretation of the results from the linear models.

Results

The control trees and the trees trained to a central leader were pruned in the same fashion on the first pruning date, with similar amounts of material removed per tree from both treatments (Table 1), but with more material removed from the ‘816’ trees than from the ‘246’ trees. Therafter only the trained trees were pruned, with a small remediation pruning in Aug. 2007 (data not shown) and more intensive pruning on four later occasions (Table 1). In total, ≈8 times more material was removed from the central leader trees than from the control trees.

The early yields of the central leader trees were consistently lower than those of the control trees. Statistically important (P < 0.05) reductions in average yield due to pruning were detected in 2011 for the ‘246’ trees and in 2012 for the ‘816’ trees (Table 2). Statistically significant increases in average yield over time were detected within all cultivars and treatments (P < 0.05) and there was a significant interaction effect (P < 0.05) of cultivar and season.

The cumulative yields of the trained trees over the first 3 years of production were 16% lower than the control trees for ‘246’ and 23% lower
The cumulative yields of ‘246’ were 67% higher than those of ‘816’ (Table 2).

The yields of the fully self-buffered control ‘246’ trees were not significantly different from those of the buffer ‘246’ trees adjacent to control ‘816’ plots in either year [4.8 vs. 6.0 kg/tree NIS in 2012; 10.1 vs. 8.2 kg/tree NIS in 2013 (se = 0.2)] consistent with a pollen parent effect. The yields of the fully self-buffered control ‘246’ trees were lower than those of the buffer ‘246’ trees adjacent to control ‘816’ plots, nonsignificantly (P > 0.05) so in 2012, but significantly (P < 0.05) so in 2013 [4.4 vs. 5.1 kg/tree NIS in 2012; 7.6 kg/tree NIS in 2013 (se = 0.2)].

The fruit harvested in one year was set from the flowering in the previous year (e.g., the 2011 harvest was set at flowering in 2010). There was more flowering in the control trees than in the central leader trees [P<0.05 (Table 2)] and more flowering in ‘246’ than in ‘816’ (P<0.05), consistent with the trends in yields. There was also a significant seasonal effect (P<0.05), and a significant cultivar x season interaction (P<0.05), again consistent with the trends in yields.

No effect of early tree training on average NIS weight was detected [P>0.05 (Table 2)]. Nuts from ‘246’ were significantly lighter than those from ‘816’ (P<0.05). Small (<1 g) but statistically important increases in nut weight over time were observed (P<0.05). Cultivar differences were inconsistent over the three seasons as evidenced by a significant interaction (P<0.05).

There was no effect of early tree training on the percentages of kernel recovery, first-grade kernel, or unsound kernel in 2013 [P>0.05 (Table 3)]. ‘816’ had higher kernel recovery and higher first-grade kernel than ‘246’ (P<0.05).

Tree heights were unaffected by early tree training [P>0.05 (Fig. 1)] and were similar for the two cultivars (P>0.05). Early tree training affected canopy widths across and along the row (Fig. 1). In essence, early tree training limited the early lateral expansion of the canopies, but the central leader trees had much the same dimensions as the control trees by the end of the experiment. Canopy widths were similar for the two cultivars (P>0.05).

The control trees of ‘816’ sustained more storm damage than the ‘816’ trees trained to a central leader (P<0.05), with 35 of the 80 control trees lodged and two trees snapped,
and 22 of the 80 trained trees lodged and three trees snapped. Early tree training had no effect on the extent of storm damage in ‘246’ (P > 0.05), with 26 of the 80 control trees lodged and five trees snapped, and 32 of the 80 trained trees lodged and no trees snapped.

By the end of the study, ≈20% of the trees initially trained to a central leader had developed codominant leaders.

**Discussion**

The early tree training of macadamia to a central leader resulted in an 18% reduction in yield over the first 3 years of production, averaged over the two cultivars (Table 2). Part of the reason for this seems to be related to the flowering habit of macadamia. Macadamia tends to flower on less vigorous branches (Wilkie et al., 2009) in shady parts of the canopy (Olesen et al., 2011). Furthermore, canopy management practices that promote strong, vertical, vegetative regrowth in mature trees inhibit flowering on a canopy volume basis (Olesen et al., 2016). There was evidence for an effect of central leader training on flowering in the raceme numbers per tree (Table 2), with more flowering on the control trees than on the pruned trees in both 2010 and 2011. It follows from the preceding arguments that the removal of subordinate branches may have reduced the propensity to flower, whereas the improved illumination of the remaining branches may have enhanced their vigor and further reduced the propensity to flower.

The response of young macadamia trees to training that commenced soon after planting was similar to that for the training of trees in the early years of production. Olesen et al. (2011) found that light selective limb removal in 6-year-old ‘849’ trees resulted in a yield penalty, whereas pruning to a central leader resulted in an even greater penalty.

Early tree training from planting slowed the expansion of the canopies (Fig. 1) and this too might have had a detrimental effect on yields, given that macadamia production tends to increase with increasing orchard light interception (McFadyen et al., 2004b, 2013).

That the trained trees had lower crop loads than the control trees may have reduced the number of flowers produced, leading to a reduction in yield.

### Table 1. Fresh weights of prunings per tree for minimally pruned control trees and trees that received early training to a central leader, for macadamia cultivars 246 and 816, planted in Mar. 2007.

|                | 2007 June | 2007 Nov. | 2008 Mar. | 2008 Sept. | 2009 Apr. |
|----------------|-----------|-----------|-----------|------------|-----------|
| **246**       |           |           |           |            |           |
| Control       | 154 a     | 141 a     | 310 a     | 127 a      | 687 a     |
| Central leader|           |           |           |            |           |
| **816**       |           |           |           |            |           |
| Control       | 186 b     | 193 b     | 46 a      | 300 a      | 118 a     |
| Central leader|           |           |           |            |           |

1 kg = 2.2046 lb; 1 g = 0.0353 oz.
2 Means followed by a different letter within a column had significantly different pruning weights per plot at P < 0.05, based on a two-way analysis of variance or t tests. There were four trees per plot, and five plots per treatment.

### Table 2. Yields, raceme numbers, and average “nut-in-shell” (NIS) weights for minimally pruned control trees and trees that received early training to a central leader, for macadamia cultivars 246 and 816.

|                | 2010     | 2011     | 2012     | 2013     | Total     |
|----------------|----------|----------|----------|----------|-----------|
| **246**        |          |          |          |          |           |
| Control        | 3.2 a    | 4.9 a    | 10.5 a   | 18.5 a   |           |
| Central leader | 1.8 b    | 4.4 a    | 9.4 a    | 15.6 b   |           |
| **816**        |          |          |          |          |           |
| Control        | 0.6 bc   | 4.8 a    | 6.0 b    | 11.5 c   |           |
| Central leader | 0.2 c    | 3.0 b    | 5.8 b    | 8.9 d    |           |

**Racemes [no./tree (natural log)]**

|                | 2010     | 2011     | 2012     | 2013     | Total     |
|----------------|----------|----------|----------|----------|-----------|
| **246**        |          |          |          |          |           |
| Control        | 255 (5.5 a) | 1,719 (7.4 a) |           |          |           |
| Central leader | 174 (4.9 b) | 1,336 (7.2 a) |           |          |           |
| **816**        |          |          |          |          |           |
| Control        | 19 (2.9 c) | 551 (6.2 b) |           |          |           |
| Central leader | 6 (1.7 d)  | 295 (5.6 c) |           |          |           |

**Avg NIS wt (g)**

|                | 2010     | 2011     | 2012     | 2013     | Total     |
|----------------|----------|----------|----------|----------|-----------|
| **246**        |          |          |          |          |           |
| Control        | 7.1 a    | 7.3 a    | 7.9 a    |          |           |
| Central leader | 7.2 a    | 7.3 a    | 7.8 a    |          |           |
| **816**        |          |          |          |          |           |
| Control        | 8.2 b    | 8.0 b    | 8.6 b    |          |           |
| Central leader | 8.3 b    | 8.1 b    | 8.7 b    |          |           |

1 kg = 2.2046 lb; 1 g = 0.0353 oz.
2 Means followed by a different letter within a column, separately for each characteristic (i.e., yield, raceme number, and NIS weight), were significantly different at P < 0.05, based on linear models. The least significant differences at P < 0.05 within and between years were 1.3 for yield, 0.4 for raceme number, and 0.2 for NIS weight.

### Table 3. Percentages of kernel recovery, first-grade kernel, and unsound kernel in 2013 for minimally pruned control trees and trees that received early training to a central leader, for macadamia cultivars 246 and 816.

|                | Kernel recovery (%) | First-grade kernel (%) | Unsound kernel (%) |
|----------------|---------------------|------------------------|--------------------|
| **246**       |                     |                        |                    |
| Control        | 34.0 a              | 96.2 a                 | 0.4 a              |
| Central leader | 34.1 a              | 96.4 a                 | 0.5 a              |
| **816**       |                     |                        |                    |
| Control        | 35.5 b              | 99.1 b                 | 0.4 a              |
| Central leader | 35.7 b              | 99.1 b                 | 0.6 a              |

Means followed by a different letter within a column were significantly different at P < 0.05, based on linear models.
help explain why the trained trees achieved canopy sizes similar to those of the control trees by the end of the experiment because branch elongation is negatively correlated with crop load (Wilkie, 2009).

Early tree training had no detectable effect on the measured nut characteristics: average NIS weight, kernel recovery, first-grade kernel, or unsound kernel (Table 3). The cropping pattern of the trees in our study was typical of that of commercial orchards, with no yield in the first few years after planting, then an exponential increase in yield in the first few years of production. However, macadamia does have large year-to-year variations in yield (McFadyen et al., 2004b, 2013) and it is not clear the extent to which these have distorted the developmental response.

The yields of ‘246’ were greater than those of ‘816’ on trees of a similar size (Table 2; Fig. 1). However, ‘816’ does have some traits that might commend it, including a larger NIS weight (Table 2), a higher kernel recovery, and a higher percentage of first-grade kernels (Table 3). The early flowering of ‘246’ was also greater than that of ‘816’ (Table 2) on canopies of comparable size (Fig. 1) consistent with the idea that ‘816’ tends to bear its racemes deeper within the canopy. The only previous work on the flowering of the two cultivars was that by Salter et al. (2005) who studied mature trees and found that the distance from the end of a branch to the first raceme encountered, whether on the primary branch or on a subordinate branch, was shorter for ‘246’ than for ‘816’, which is consistent with our results. The branches of ‘246’ are more recumbent than those of ‘816’, and the interplay between architecture, floral physiology, and microclimate deserves attention.

The yields of the ‘816’ trees adjacent to ‘246’ trees were greater than those of the fully self-buffered ‘816’ trees, consistent with a pollen parent effect. The same was not true of ‘246’, with similar yields for trees adjacent to ‘816’ trees and fully self-buffered trees. The difference between the cultivars may relate to self-compatibility; ‘816’ is less self-compatible than ‘246’ (McConchie et al., 1996).

Early tree training to a central leader improved the resistance of the upright cultivar 816 to storm damage, but had little effect on the susceptibility of the more spreading cultivar 246. Most of the damage was in the form of the lodging of trees, which crudely equates with the drag of the whole canopy. The incidence of tree snapping, which included both clean snapping and tree splitting, two quite different forms of mechanical failure, was too low to analyze separately.

In summary, the current industry recommendation of training young trees to a central leader ought to be reconsidered. Minimal pruning of young trees, to remove poor crotch angles for the sake of structural stability, appears to be a better option. The experiment described here ended with the 2013 harvest. The plots were immediately reallocated for a trial into the use of selective limb removal to control tree height. Macadamia trees are vigorous and productive for many decades. Our goal is a comprehensive canopy management strategy for the productive life of the trees.

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