2022

Avocado canopy management literature review

Helen Hofman
Senior Horticulturist
Queensland Department of Agriculture and Fisheries

Queensland Government
Hort Innovation
Strategic levy investment
AVOCADO FUND
Avocados Australia

Contents

1. Introduction .... - 3 -

What 'canopy management' means in this review .... - 3 -

The importance of canopy management to profitability .... - 3 -

2. Avocado physiology and implications for canopy management .... - 4 -

Light needs .... - 4 -

Avocado leaves are short-lived .... - 5 -

Distinctive flush patterns .... - 5 -

Indeterminate flowering and fruit:shoot competition .... - 6 -

Alternate bearing .... - 6 -

3. Canopy management principles .... - 7 -

(a) Optimise light interception .... - 7 -

(b) Ensure light distribution in the canopy .... - 9 -

(c) Optimise structure .... - 9 -

(d) Allow operational efficiency .... - 10 -

Options for applying principles .... - 10 -

4. A brief history of canopy management trends .... - 10 -

5. Planting density .... - 11 -

Tree removal .... - 11 -

6. Tree shaping .... - 13 -

Central leader shaping .... - 13 -

Cylindrical or open vase shaping .... - 14 -

'Stump' shaping .... - 16 -

Trellised shapes .... - 16 -

Cultivar differences .... - 16 -

7. Canopy manipulation .... - 20 -

Early tree shaping .... - 20 -

Stumping, stag-horning or top-working .... - 21 -

Hedgerow mechanical pruning .... - 21 -

Selective limb pruning .... - 22 -

Window pruning .... - 25 -

Tip pruning ... - 25 -

Timing of pruning ... - 25 -

Follow up/summer pruning ... - 26 -

Pruning side effects ... - 26 -

Removal of dead wood ... - 26 -

Rootstocks ... - 27 -

Root pruning or root restriction ... - 27 -

Plant growth regulators for reducing vegetative growth ... - 28 -

Plant growth regulators for increasing complexity ... - 32 -

Girdling ... - 32 -

Ground cover ... - 33 -

Water and nitrogen management ... - 33 -

8. New technologies to aid in decision making ... - 33 -

9. Comparative performance of canopy management approaches ... - 34 -

Definitions and abbreviations ... - 40 -

References ... - 41 -

A note on formatting in this review:

- Each section begin with a summary of its content in **bold blue type**
- More detailed research or practical advice are contained in text boxes like this one
- Cultivars and rootstocks are indicated in single inverted commas 'Thus'.
- Abbreviations and definitions can be found at the end of this paper.

1. Introduction

What 'canopy management' means in this review

In this review, canopy management refers to interconnected strategies that are categorised as:

- planting density options
- tree shaping styles, and
- canopy manipulation options, for example, pruning and plant growth regulator strategies.

The importance of canopy management to profitability

There is very little available data on the contribution of canopy management strategies to orchard profitability.

Anecdotal evidence of decline in yield from farms where trees become overcrowded is the main evidence of the importance of canopy management (see, for example, France, 1947; Crane *et al.*, 1992; Stassen *et al.*, 1999a; Thorp and Stowell, 2001).

A benchmarking exercise into avocado farm profitability in Australia 2015 found that canopy management practices were the second most important area of activity (after mulching, drainage and *Phytophthora* management) for the 10 most profitable growers surveyed when compared to the remainder of the benchmarking group (Hall, 2015).

Two studies that attempt to quantify some aspects of the economic benefits of canopy management are:

- Hofshi (1999) estimated the differences in picking costs and effects on returns to the grower for short (<15') versus tall trees. Using an example, he estimates shorter trees returned 19% to 23% more to the grower, depending on the number of 'picks'. The estimate, however, assumes equal yields per hectare from tall and short trees.
- Dense canopies can limit the penetration of pesticide and fungicide, as well as potentially providing a moist microclimate inducive to pest proliferation. Everett *et al.* (2007) found that an index describing canopy density and the number of dead branches in the canopy of a population of 'Hass' in New Zealand was significantly related to the incidence of body rots (but not stem-end rots).

2. Avocado physiology and implications for canopy management

Many of the features that allow the avocado to adapt to its natural rainforest or cloud-forest conditions make it challenging for canopy management. These features include vigorous growth, short-lived leaves, terminal flowering, a habit of flowering on the last-formed growth units, and 'small gap specialisation', that is, a pattern of rapid growth into light gaps.

Light needs

Improving light levels through the canopy is one of the main aims for canopy management for all tree crops. However, avocado is a substory rainforest species, adapted to low light conditions, meaning avocado leaves function well at low light availability, and some shade does not appear detrimental to vegetative or fruit growth. Nevertheless, several studies show that photosynthesis, flowering intensity and fruit quality are higher in the outer canopy.

Studies generally agree on a low light requirement for avocado, with light saturation point measured between 20 to 33% of full sunlight, although Whiley found this to be 50% for unstressed trees (Wolstenholme and Whiley 1999). The light saturation point is the level of light which produces the highest photosynthesis rate: increasing light levels beyond this point does not result in increased photosynthesis. The following studies have been reported:

- Scholefield *et al.* (1980) found mature leaves of container-grown plants ('Fuerte') had maximum rates of photosynthesis of 0.30 mg CO_2 $m^{-2}s^{-1}$ at ~ 500 µmol $m^{-2}s^{-1}$, *i.e.* 20 to 25% of full sunlight. Measurements in the field gave a similar light saturation level, but lower rates of maximum photosynthesis: 0.11 to 0.12 mg CO_2 $m^{-2}s^{-1}$. The authors attributed this difference to lower temperatures outdoors (the study was done in winter). Interestingly, some leaves inside the canopy were photosynthesising at rates of up to 0.10 mg $m^{-2}s^{-1}$ at a very low light levels: 60 µmol $m^{-2}s^{-1}$.
- Bower found that maximum rates of photosynthesis in container-grown trees (cv. Edranol) of ~ 0.30 mg CO_2 $m^{-2}s^{-1}$ were reached at about 20% of full sunlight (full sunlight = 1100Wm-2) (Bower 1978, Bower, Wolstenholme et al. 1977.
- Wolstenholme and Whiley (1999) cites unpublished data by Whiley of light saturation at 1110 µmol quanta·m-2·s-1, or over 50% of full sunlight, for unstressed trees.
- A study by Chirachint and Turner (1988) showed that reduced light did not affect the growth of 2-year-old potted 'Fuerte' trees in a six-week study under glasshouse conditions. Plants were grown either at maximum PPFs of ≈ 1350 µmol quanta m-2 s-1 (full sunlight in the glasshouse at noon on a clear day) or under shade which reduced PPFs to ≈ 725 µmol quanta $m^{-2}s^{-1}$. The lack of differences was probably because much of the time the light levels were above the maximum light saturation point.

Despite this low light requirement, leaves on the outside of the canopy were found by Shezi *et al.* (2019) to have more photosynthetic efficiency, leading to an increased rate of dry matter production which was linked to earlier fruit maturity.

In addition, studies suggest flowering is more prolific and advanced in high light environments. Wolstenholme and Whiley (1999) stated that only well-lit peripheral buds undergo floral induction in autumn, but no data was provided to support this. Dixon *et al.* (2007) report the best fruit set was on the outer edge of the canopy and in the full sunlight. A study by Aounallah *et al.* (2017) on 'Hass', 'Fuerte' and 'Bacon' in Tunisia concluded that shade delays flowering by up to 20 days. In addition, their study showed the overlap of female and male phases of flowers was higher on the sunniest face of the tree (i.e. where there is more light and higher temperatures), and this resulted in a higher percentage fruit set.

Hofman *et al.* (2021) reported that their light studies found that light levels had a positive but weak linear correlation with the number of axillary inflorescences per shoot (a measure of flowering intensity), the time of floral expansion and time of anthesis and the length of vegetative growth of the shoot emerging from indeterminate inflorescences. However, there were no such relationships between PAR levels and fruit set or retention. They hypothesized that fruit set inside the canopy is not disadvantaged by the low levels of light because of the transport of resources between branches, and that fruit that set in shaded parts of the tree may have some advantages, including the protective effect of the canopy, the reduced rate of vegetative growth which may compete with fruit set, and the later timing of set (due to later anthesis), meaning set is at a time when the competition for resources is less fierce.

Woolf *et al.* (1999) found that fruit in the sun had higher dry matter content than fruit in the shade. (Shezi *et al.*, 2020a; Shezi *et al.*, 2020b) found fruit on the outside of the canopy had an average dry matter of 28.9 % compared to 26.9 % for fruit within the canopy (i.e. fruit maturity in the canopy was delayed by about two weeks). Whiley *et al.* (1992) found that the skin of fruit photosynthesizes and thus fruit contribute a small amount of their own carbon requirements.

Avocado leaves are short-lived

Avocado leaves adapt quickly to increasing light but are short-lived and older flushes less efficient, meaning canopy management needs to allow for new growth for optimum performance.

A study by Osmond *et al.* (2011) found that old shade leaves can adapt to high light levels after pruning in as little as 3-10 days. Mickelbart *et al.* (2007) found that as the new flush expands, photosynthesis reduces in older leaves and these leaves also tend to abscise. Studies by Liu *et al.* (2002) show that photosynthesis on the previous flush begins to decline once a new flush is mature.

Distinctive flush patterns

Avocado trees produce vegetative shoots in distinctive flushes. Flowering is on flush from the previous season. Canopy management strategies need to ensure retention of sufficient flowering shoots plus sufficient time for these shoots to develop to maximise crop in the following year.

Thorp *et al.* (1993) found in a study of 'Hass' in South Australia that flowers were produced on the terminal or last-formed flush, which was predominantly a summer or autumn flush in the area of study.

There appear to be some climatic differences in whether the spring, summer or autumn flush is predominantly the flowering flush. In New Zealand the spring flush is more important (Dixon, 2007; Cutting, 2003; Dixon *et al.*, 2007). This appears to be because the spring flush in an on-year tends to be predominantly determinate, and this is important in determining the final crop load (Dixon *et al.*, 2007; Cutting, 2003).

Indeterminate flowering and fruit:shoot competition

The propensity of avocado to indeterminate flowering exacerbates competition for resources between vegetative growth and fruit set/ development in spring, meaning canopy management needs to avoid exacerbating vegetative growth at this time.

An indeterminate shoot is one that develops an inflorescence with a vegetative tip that emerges from the apex over the spring period. A determinate shoot has an inflorescence but no vegetative shoot. Generally, indeterminate shoots predominate in avocado.

There is substantial evidence for avocado of competition for resources between vegetative growth and fruit set/ development in spring, including:

- studies demonstrating better spring fruit set on determinate shoots (Salazar-Garcia and Lovatt, 1998; Thorp *et al.*, 1994; Hofman *et al.*, 2021), although Evans *et al.* (2010) found no difference for 'Hass' in New Zealand and Dixon *et al.* (2007) found set increased on determinate shoots only in an 'on-year';
- studies demonstrating reduction of vegetative growth with application of plant growth regulators at mid-bloom increases yield and/or fruit size (see section on 'Plant growth regulators for reducing vegetative growth' on page - 28 -); and
- studies demonstrating improved spring fruit set when vegetative shoots are removed (Biran, 1979; Cutting and Bower, 1990; Zilkah *et al.*, 1987; Hofman *et al.*, 2018).

While there are some reports that the gains made in fruit set in spring by these strategies are mitigated by increased drop in summer, resulting in no increase to final yield (Cutting and Bower, 1990; Wolstenholme *et al.*, 1990; Hofman *et al.*, 2018), this physiological aspect factor informs canopy management in two main ways. These are:

- the use of plant growth regulators to reduce spring vegetative growth and thus promote increased fruit set, and
- the timing of pruning in winter to reduce the likelihood of excessive vegetative growth at the expense of fruit set in spring.

These two aspects are discussed in sections 'Plant growth regulators for reducing vegetative growth' (page - 28 -) and 'Timing of pruning' (page - 25 -).

Alternate bearing

Avocado trees can be alternate or biennial bearers. Trees carrying a small crop can have excessive vegetative vigour; whereas a heavy crop tends to retard vegetative growth. Canopy management strategies are therefore linked to strategies to reduce biennial bearing.

Mickelbart *et al.* (2012) found more shoot development (particularly of the summer flush) occurring in a year with virtually no crop than in other years. Analysis by Hofman *et al.* (2021) of shoot data confirmed that the presence of a fruit tended to repress summer vegetative growth (at least in a heavy crop load year). While summer growth on non-bearing shoots was on average somewhat longer, had slightly more leaves and had more branching than growth on bearing shoots, the main effect was to repress summer flushes entirely. However, this effect was not 'black-and-white': on 29% of non-bearing shoots there was no bud release and on ~40% of bearing shoots there was bud release. This suggested to the authors that the effect is not purely localized, but signals or resources are shared across branches or trees.

3. Canopy management principles

The key principles for canopy management can be summarised as (a) optimise light interception, (b) ensure light distribution within the canopy, (c) optimise structure, and (d) allow orchard efficiency. There are many canopy management options for applying these principles.

(a) Optimise light interception

Light interception is the term used for the amount of light captured by trees in an orchard, rather than falling on or through the canopy to the orchard floor. The principle for orchard design is to optimise light interception, that is, to maximise light interception without detrimentally affecting yield.

The main determinates of light interception are plant spacing, tree height and tree shaping. There is limited advice published on the specific limits or interactions of these factors. Instead, a range of 'rules of thumb' have developed from the experience of practitioners – these are outlined in the box below.

One set of quantitative data is provided in a study at Childers, Central Queensland, by Wilkie *et al.* (2019) of various 'Hass' orchard blocks with differing tree sizes, planted at conventional densities of 10 or 11 m rows and 5 m tree spacing. This demonstrated that total light interception >80-84%% led to either yield decline or a yield plateau (the trend of the data was inconclusive, see Figure 1). Data provided shows that, at this planting spacing, trees 8.3m high and 8.1m wide were at the 80% light interception level (Table 1): this effectively provides the limits of canopy size at this spacing. No similar studies for other spacings were found in this review.

Table 1 Canopy dimensions and canopy volume per hectare and total light interception in 2015 for trees planted in 10/11m rows at 5 m spacing from Wilkie et al. (2019)

Canopy height (m)	Canopy width (m)	Canopy volume (m3/ha)	Total light interception (%)
3.4	3.3	3,642	22
5.0	5.3	12,604	51
8.3	8.1	31,650	80
8.8	9.9	38,100	89

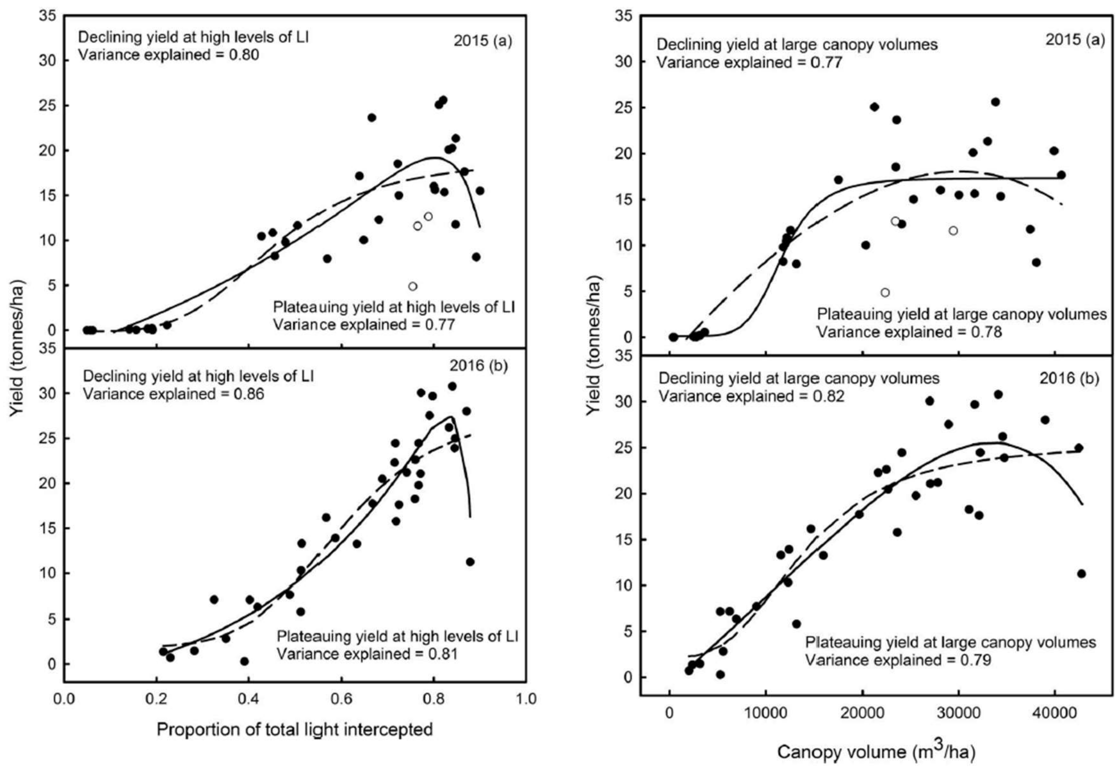

Figure 1 Declining or plateauing yield in two years (2015 top and 2016 bottom) with higher levels of total light intercepted (left) and higher levels of canopy volume (right) from Wilkie et al. (2019).

Comparative modelling by Hadari (2004) of the light regime in avocado orchards suggests that high density systems that feature close planting, lower tree height and angled canopy surfaces (pruned) have high light interception values (although not as high as hedgerows) and the highest levels of light distribution in the lower part of the canopy.

Orchard design: Rules of thumb to ensure optimum light

A set of rules of thumb are often quoted in published advice on orchard design. In most cases, these are based on experience or other tree crops and no data is provided in support of these rules.

- Plant north-south to maximise the amount of intercepted light (Stassen *et al.*, 1995a; Hadari, 2004; Stassen, 1999b)
- Maximum tree height should be 80% of row width (Stassen *et al.*, 1995a; Hofshi, 2004; Stassen *et al.*, 1999a; Snijder *et al.*, 2000; Stassen, 1999b). Height should be less than 80% where rows are not north-south orientated or on a slope (Stassen *et al.*, 1999a; Snijder *et al.*, 2000). Snijder and Stassen (1999b) suggests a rule of 70% but no data is provided to support this more stringent level. Mena (2005) suggests that overcrowded low density orchards (100-200 trees/ha) need to be pruned so height is no more than 70% of row width.
- Maximum tree height should be twice the free working space between rows (Stassen *et al.*, 1995a), or 1.5 to 2 times (Wolstenholme and Whiley, 1995).

(b) Ensure light distribution in the canopy

The growth habits of avocado (short leaf life, indeterminate flowering, regular flushes and high levels of small branch death) foster a thick outer canopy with dark empty centres if the canopy is not managed. In orchard environments, the thicker outer leaf layer can mean that light does not penetrate very far into the canopy. Canopy manipulation strategies can exacerbate this (e.g., potentially, hedging) or improve this (e.g., potentially, selective pruning or window pruning).

Hadari (2004) found that, in hedgerows of 'Hass', light was extinguished to 20% within 20cm to 1 m of the canopy surface.

Hofman *et al.* (2021) measured light penetration into selectively pruned, central-leader shaped 'Hass' trees at low, medium and high density and also found light levels dropped to below 20% at 50-100cm on average, except for high density trees ~2 m wide (1 m into each row) (Figure 2).

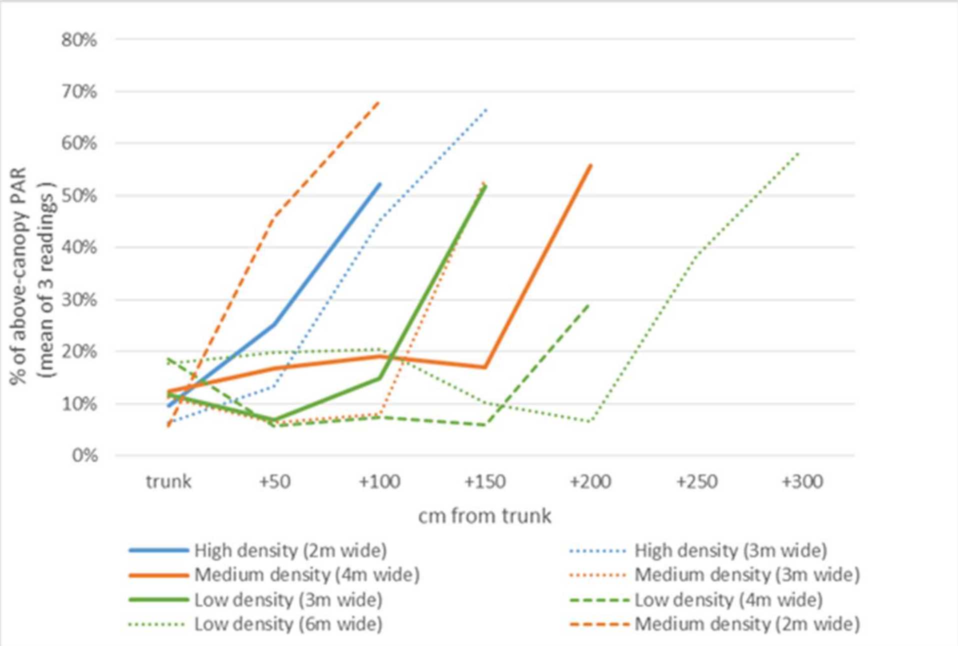

Figure 2 Mean % of above-canopy PAR in 50 cm intervals through the canopy (spring 2018). Solid lines show means of trees of the same canopy width (n=3 for high and medium densities, n=4 for high density). Dotted or dashed lines show single trees (presented separately because their canopy width was atypical). All trees 'Hass' on 'Velvick' rootstocks. 'PAR': photosynthetically active radiation, from Hofman et al. (2021).

(c) Optimise structure

The concept of optimising structure -- to balance maximising fruiting sites, provide sufficient 'leaf' to support developing fruit, and minimise the respiration costs of non-productive wood structures such as trunk and branches -- is mentioned in some avocado literature, but overall does not receive as much attention as other principles, possibly because it is not well understood or because it is not considered problematic.

Mena (2005) notes that 'increasing complexity' to maximise fruiting sites for this terminal bearing species is an important principle. Some of the strategies outlined below mention this as a principle.

Retaining sufficient leaves to 'feed' fruit is also important. Leaf: fruit ratio was calculated by Thorp (1992) at 104:1, by Köhne (1989) at 84:1 and by Hofman *et al.* (2021) at 159:1 and 113:1 in consecutive years.

Another aspect of this principle is minimising the respiration costs of woody structures which can be significant in large trees (Givnish, 1988). Hofshi (2004) states as a principle: 'Minimise the amount of structure that needs to be supported'.

(d) Allow operational efficiency

Operational principles include ensuring access and efficiency for harvesting, weed management, maintenance of ground cover and spraying.

These are generally implicit in the literature and are rarely discussed. This principle is relatively less important in growing regions where labour costs are low. Hofshi (2004) also emphasised the need to maintain access by bees and ensure spray penetration.

Options for applying principles

There are several options for canopy management which can theoretically apply these four principles. To provide context, the broad historical trends in canopy management are first described below, followed by more detail on the various options.

4. A brief history of canopy management trends

The earliest avocado literature, mostly written by practitioners in the USA beginning in the 1940s, deals with trees in low density plantings with minimal canopy management action. Trees were planted in the range 10x8m to 12x9m (92-100 trees/ha) (Whiley *et al.*, 2013). Francis (1994) cites orchards (albeit unusual) in California and South Africa which had as few as 20 trees/acre or 48 trees/ha (note that at this spacing the trees were not overcrowding). The focus of this early literature was on strategies to maintain orchard productivity once trees start to crowd. It provided advice (usually unsupported by data) on three aspects: initial tree shaping when trees are small, thinning out of interplanted trees when crowding becomes an issue, and pruning.

Over time planting densities have increased e.g. in central Queensland 10 or 11 metre rows with 5m tree spacing are now typical (Wilkie *et al.*, 2019). With more closely planted trees, hedging and mechanical pruning became an option in the 1990s, with reports on its use published through to the early 2000s. Subsequently, adverse effects of hedging led practitioners to explore more selective pruning options.

Literature on canopy management in higher density systems also begins to appear in the 1990s, with studies in South Africa, Chile, the USA and Israel. The focus of these publications tends to be on tree shaping, with an initial emphasis on central leader shapes, shifting in later years to a vase or cylindrical shapes in reports from Chile and the USA.

Information on the use of plant growth regulators emerges from the 1980s onwards, applicable in both low- and high-density systems. Research was conducted in Australia, New Zealand and South Africa, with less input from the USA where many of these products are not legally permitted.

Most recently, some research into the use of remote-sensing technology to assist in canopy management decisions has begun to emerge.

5. Planting density

Planting density is a key factor in determining not only the method but also the intensity of canopy management. In general, low-density plantings require minimal canopy management in the early years as the trees are left to develop a natural shape. There are a range of strategies applied when trees begin to crowd, including tree removal. Higher density plantings require earlier and more frequent intensive intervention, including shaping (Hofshi, 2004; Mena, 2005).

The literature on tree removal as a canopy management option is reviewed below, but a full assessment of planting density options is outside the scope of this review. Those interested in this aspect may find the review of high-density plantings by Menzel and Le Lagadec (2014) useful, as well as the more recent report by Mitchell (2019) on progress with high density avocado production in Chile and the USA.

Tree removal

A planting density option which receives much attention in the literature is the strategy of planting at high densities and then removing trees (called ‘temporary’ ‘interplant’ or ‘filler’ trees) when the trees begin to crowd and/or yield begins to decline. Many practical approaches are suggested, but few discuss the economic aspects of this approach, i.e. tree purchase costs and removal and disposal costs. A popular strategy is to first ringbark or girdle the trees to be removed for a final boost to yield before removal. Overall, reports suggest this strategy is successful in returning yields, after one or two years of depressed yields.

Of the listed studies below, only three -- Francis (1971, Crane *et al.* (1992) and Toerien and Basson (1979a) -- provide data on yield effects.

- Barrett (1946), recommended, for ‘Fuerte’, square plantings at 60-70 ft, with interplantings at 30 ft that are removed when the trees begin to crowd (at 15-18 years old).
- Averett (1949) described a complicated system of removal (too complex to describe here) which begins with identifying each individual tree that is healthy and produces good crops, and then developing a pattern of removal which minimises loss of these.
- Marsh (1941) described a system in which every second tree is initially (at ~ 7 years), pruned heavily or ‘cut back’ and then removed in ~ year 11.
- Platt (1976) recommended progressive thinning by first removing alternate diagonal rows, then a second thinning by removing every other row, and a third thinning, if necessary, removing every other diagonal row of the remaining trees in the block. By this method, trees set at an initial spacing of approximately 6 m would be spaced at about 8 m following the first thinning, 12 m following the second and 15 m following the third thinning.
- Francis (1971) reported on an orchard of ‘Fuerte’ that was thinned by 50%. Production initially decreased then improved after three years to meet the maximum levels achieved before crowding began to depress yields. A graph of this pattern was presented in this article but numerical yields were not cited.

- In Florida, Crane *et al.* (1992) rejuvenated crowded orchards of 'Lula' and 'Booth 8' by topping at 12, 16 or 22 feet and, for some treatments, removing every second tree in a diagonal pattern. Trees topped to 22 ft with and without tree removal produced more fruit per acre (119 and 108 bu, respectively) than trees topped at 9 ft (43 bu/acre) and 16 ft with trees removed (86 bu/acre). 'Booth 8' trees topped generally produced fruit 18 months after topping. More fruit was produced in 'Booth 8' plots topped to 16 and 22 ft with trees removed (469 and 464 bu/acre, respectively for two years combined) than those topped to 9 ft with trees removed and 22 ft with no trees removed (130 and 249 bu/acre, respectively for two years combined). Confused, dear reader? In short, they recommended topping 'Booth 8' at 16 or 22 ft *with* tree removal; but topping 'Lula' at 22 ft *without* tree removal. Topping and removing trees increased the amount of fruit produced in the middle and lower thirds of the tree canopies.
- Toerien and Basson (1979a) trialled three methods of tree removal in alternate diagonal rows of 7-year-old trees ('Edranol') in South Africa in a 6 m x 6 m spaced planting: staghorning; removal at ground level and killing roots with Roundup; and removal at ground level and removing roots with soil ripping. For the 'ground level' removal treatments, yields per tree for the remaining trees increased by 50% in the following season compared with trees at the original planting density (Table 2). However, yields per hectare declined because of the number of trees removed.

  They also applied some ringbarking treatments (a 9cm strip was removed) and a top pruning treatment to trees which were later to be removed after harvest with the aim of a temporary (one year) boost to yield (later years of data not provided). The use of a 'low ringbark' on the trunk (just above the graft union) gave a temporary boost to yield but not a 'high ringbark' (at 5m high) or 'top pruning'.

Table 2 Production in the first year after different tree removal, ringbarking and pruning treatments from Toerien and Basson (1979a)

Treatment	**Kg/tree**	**Total prod (kg)/ha**
Control (no tree removal)	74	20,424
Tree removal by staghorning	86.9*	11,992
Tree removal at ground level and 'Roundup'	110.8*	15,290
Tree removal at ground level and ripping	104.0*	14,352
Low ringbark (above graft union but low on trunk)	102	24,288
High ringbark (at 5m)	66.6	19,402
Top pruning (at 5m)	12.6	11,950

** Data is for remaining trees*

Removal of trees does not mean canopy management strategies from that point are unnecessary. Stassen *et al.* (1999a) report that tree removal with no follow up strategy meant trees grew to fill the space within two years.

6. Tree shaping

Central leader shaping

Central leader shaping, theoretically the best shape for light maximisation, has been promoted by several authors, particularly for South African orchards. Some reports are less favourable. Some of the more upright cultivars may be more suited to this shaping.

The use of central leader pruning has proved productive for many tree crops. In theory, this shape – a narrower top and wider base - is the best for light interception in an orchard environment and its theoretical benefits are espoused in a range of articles including Martin and Witney (1995) and Hadari's (2004) modelling exercise. The latter found that to maximize total intercepted radiation, maximize light intensity and maximize the total radiation at the lower 2 m of the canopy, avocado tree height should be reduced, trees should be closely planted, and trees should be pruned at a sharp angle.

The box 'Creating a central leader shape' below provides details of pruning to achieve this shaping.

Stassen and Snijder and colleagues published a range of reports in the 1990s on the use of central leader shaping for 'Hass' in high density plantings in South Africa, with the aim of increasing precocity and early returns and maintaining productivity over the long term (Stassen *et al.*, 1995a; Stassen, 1999a; Stassen and Snijder, 1996a; Snijder and Stassen, 1998; Stassen *et al.*, 1999b). Early yields (first four years) were comparatively higher in their high density, central leader systems than in lower density plantings (Stassen, 1999a). Interestingly, Whiley and Anderson (2002) remarked in a report on a study tour of South Africa in 2002 that despite this extensive publication record promoting central leader shaping, they saw no evidence of farmers adopting this approach. Instead they provided two examples of famers that pruned alternate sides with mechanical saws (see section on 'Hedgerow mechanical pruning' on page - 21 -) and used uniconazole to retard both spring and summer growth (see ' Plant growth regulators for reducing vegetative growth' on page - 28 -).

Ernst and Ernst (2011) report on central leader pruning for 'Maluma'. No yield or size data was provided. Trees were planted on 7.5 m rows with 3 m tree spacing in a 'tramline' design, i.e. a second row of trees was planted on the diagonal of every row, 2 m from the 'main' row. This allows the eventual removal of the second row of trees if necessary. At the time of reporting, year 5 for the oldest trial, the authors had not found it necessary to use PGRs to control growth.

Central leader shaping in high density orchards was also promoted by Rueben Hofshi in California for upright varieties with natural central leader architecture such as 'Gwen', 'Reed' and 'Lamb Hass' at 2.25 x 2.25 m spacing. Whiley and Anderson (2002) report one 'Reed' orchard yielded 6.5, 26.0, 65, and 81.7 t ha-1 in the third to sixth years from planting, respectively. However, comparative information on these systems does not appear to be available.

Mitchell (2019) reports that in California high density growers use an annual 'rule of thumb' for height of the branch to form a triangular tree shape i.e. if a branch is at knee height the cut is to be made 50cm from the trunk; if the branch is at waist height it is to be cut 25cm from the trunk; if the branch is above shoulder height it is to be cut off at the trunk. This creates a triangular tree shape over time. Pruning is done directly after harvest to allow regrowth from dormant buds to reach a suitable size for girdling in the late autumn on early pruned branches and possible flowering in the spring of the same year.

Hofman *et al.* (2021) report on a trial of planting densities of 'Hass' planted at low, medium and high densities. Trees at the medium and high densities were pruned to central leader shaping. The higher density plantings in this system failed to produce yields per hectare that matched the low-density planting (for details see section on 'Comparative performance of canopy management ' on page - 34 -). The authors state that the reasons for this may include the pruning of tops and close planting leading to excessive umbrella shaped growth at the tops. This growth may have competed with fruit for resources as well as shading lower canopies. The authors also reported that where pruning produced light gaps in the canopy, trees rapidly sent up highly vigorous watershoots and/or strong sylleptic growth. Stassen and Snijder (1996b) also found that the improvements to light levels from pruning in winter were short-lived, with light levels at 1 m from the edge of the canopy reverting to almost the same pre-pruning levels by summer.

Martin and Witney (1995) saw this approach as an alternative to tree removal (see 'Tree removal' on page - 11 -). They recommended stumping the tree at 300-600 mm, selecting one shoot to grow out of the stump and training it to form a central leader. No yield or growth data was provided to support this strategy.

Creating a central leader shape

Stassen and Snijder (Stassen and Snijder, 1996a; Snijder and Stassen, 1997) and Ernst and Ernst (2011) describe the practical principles for pruning of central leader systems:

- Remove strong vertical growth that will affect the central leader (Ernst and Ernst, 2011; Stassen and Snijder, 1996a).
- Side branches that are more than a third of the thickness of the leader must be bent or cut back 50% to a bud or preferably to a horizontal side branch (Stassen *et al.*, 1995b; Snijder and Stassen, 1999b)
- Branches more than half the thickness of the leader must be totally removed. Cut it right back to the leader i.e. leave no stub (Stassen *et al.*, 1995b; Snijder and Stassen, 1999b)
- Side shoots must be tipped at 200 mm to force lateral shoots if they are not developing normally. (These laterals develop into the future fruit bearers) (Stassen *et al.*, 1995b)
- Restrict tree height by cutting back the leaders to a lower weaker relatively upright side shoot.
- Don't remove more than 20% of canopy (Snijder and Stassen, 1997).
- Remove branches that cross over other branches, or head inwards towards the trunk (to improve light penetration)(Ernst and Ernst, 2011).
- Ensure that horizontal branches are evenly dispersed in a spiral formation. No branch should be directly above another branch (Stassen *et al.*, 1999b).

Cylindrical or open vase shaping

Cylindrical or open vase shaping has been used successfully to rejuvenate crowded trees. It has also been successfully used in high density plantings. It improves the light environment. This shaping appears to be more suitable for varieties with spreading structures.

This approach was initially promoted in California by Greg Partida, referred to in that state as the 'Cal Poly' style, and was considered suitable for planting at 20' x 20' on slopes (Witney, May 2001).

Stassen (1999b) recommends this approach to rejuvenate heavily crowded trees. A drastic pruning strategy for overcrowded orchards is recommended by Snijder *et al.* (2000), as follows: Select one to four vertical leaders and head these leaders at a height of 3 to 4 m in about July. Cut the angled leaders of other branches back to achieve a pyramidal shape. Cut the branches at the base that grow into the work-row to about 1.5 to 2 m from the main stem and at the top to about 500 mm. This will ensure that an open V-shape is created in the work-row. In October/November, shave the regrowth when ~ 200 mm long to ensure enough branching (i.e. complexity). The regrowth after this shave can be sprayed with a plant growth regulator when the shoots are 50 mm long. Another shave can be done in December/January to ensure enough complexity, and again the regrowth can be sprayed when 50 mm long.

Creating a vase shape

- Select three or four well-spaced major limbs as the main structure (Mitchell, 2019; Witney, May 2001)
- Cut back or remove over-dominant leaders, leaders that encroach on neighbouring trees, and poorly positioned branches (crossing one another, etc) (Witney, May 2001)
- Keep overall tree height to 15 to 20 ft (Witney, May 2001) or 2 m (Mitchell, 2019))
- Select side branches (to carry fruit) around the tree, at a wide angle to the main limbs, and no more than 1/3 the diameter of the main limbs at their point of attachment (Witney, May 2001)
- Remove vigorous vertical growth, including a second pruning round each winter (Mitchell, 2019)

Chile also provides examples of the use of this shaping in high density orchards. These orchards are often on poor soils and steep slopes with excellent drainage (Mena, 2005). Initially, in Chile high density plantings strove to produce a conical tree shape through central leader shaping (Mena, 2005; Hofshi, 2004). Then, based on work by Reuben Hofshi in California, GAMA promoted plantings to 3 by 3 m, aiming for a tree height and width of 2m and a cylindrical shape (Mena, 2005). Orchards are planted without interows. Trees are topped at a height of 2m, to ensure light penetration to the ground floor. As part of the Chilean (but not the Californian) system, the plant growth regulator (uniconazole) is used to reduce growth (see section on 'Triazoles' on page - 28 -).

'Stump' shaping

Stump shaping describes shaping down to the stump with regular pruning to constantly stimulate new growth. There is very little information published on this strategy.

Mitchell (2019) reported on a canopy management strategy seen in high-density planting with the focus on stimulating new growth and complexity. Old growth is restricted to as small a volume of tree structure as possible – that is, the stump itself – from which new growth is stimulated. After a certain height is reached, or if a branch is problematic, branches are removed down to the stump with no concern for the shape of the tree. Foliar applications of PGRs were used at flowering to aid in fruit set and perhaps once more during the season to control vegetative flushing. No data was provided on the success of this strategy.

Trellised shapes

There is a dearth of published reports about trellised avocado systems, so undertake with caution!

Mitchell (2019) mentioned work done by Ernst in South Africa with 'Maluma' comparing vertical and Tatura (V- shaped, double planted) trellises at 800 and 1200 trees/ha with an unspecified control. He cited 2 years of yield data in which the highest yields from the five options are from the higher density Tatura plantings.

The high-density treatment in the planting density trial of 'Hass' reported by Hofman *et al.* (2021) was a central leader shape tied to a single-plane trellis, with some limb-bending in the early years of training. The authors reported the support of the trellis meant trees grew rapidly in height compared to low density treatments. Regularly pruning of height to 4m resulted in rapid umbrella-like growth at the tops e.g. by harvest time in year 5 after planting, the trees at high density were on average 5.4 m high compared to 5.0m for the unpruned trees at low density (ns, P=.142). High density yields per hectare were lower than low density yields per hectare (see Section 'Comparative performance of canopy management ' on page- 34 - for details)

Cultivar differences

In choosing a tree shape for canopy management, be aware that cultivars vary in vigour and tree shape, making some more suitable to different shaping and/or planting densities.

The most detailed published study into differences in tree form and growth patterns of avocado cultivars is Thorp and Sedgley (1993a). They examined shoot growth and tree architecture in five cultivars at two locations. The characteristic forms of each cultivar were found to be due to differences in the number and lengths of branches, and of the relative dominance of proleptic and sylleptic shoots. Sylleptic axillary shoots grow at the same time (that is, in the same flush) as the extension of the main axis; proleptic shoots grow in the next flush, that is, after a resting period. 'Fuerte', 'Gwen' and 'Reed' produced large numbers of sylleptic shoots, few major limbs and relatively short axillary branches, leading overall to upright trees. 'Sharwil' exhibited strong apical growth with relatively few sylleptic shoots, many major limbs, and long and numerous proleptic axillary shoots i.e. a spreading form. 'Hass' was intermediate between 'Sharwil' and 'Reed' at the same location. There were differences between the environments: 'Hass' trees in Queensland were more upright and had fewer and longer major limbs than 'Hass' trees in South Australia.

The authors concluded that the more compact tree forms are related to a dominance of sylleptic growth and suggested plant growth regulators or rootstocks could be used to encourage this type of growth. In this review, no studies were found that report on use of plant growth regulators for this purpose. Pruning may also affect the relative proportion of sylleptic shoots. Cutting *et al.* (1994) compared pruning cuts through the bud ring with pruning cuts midway in the rhythmic flush section and found that the latter resulted in more sylleptic growth, but no data was provided to illustrate this.

Studies which provide information on differences in canopy management for individual cultivars include the following:

- **'Bacon':** Razeto and colleagues (Razeto *et al.*, 1992; Razeto *et al.*, 1995) chose the cultivar 'Bacon' for high density planting due to its upright and 'stunted' tree form and precocious production. They reported a production of 43.7 tonnes/ha in the seventh year of a 4m x 2m planting, with declines in production evident in the eighth year. No pruning or planting growth regulators were used. The planting was planned for 12 years but this review found no report on final results.
- *'***Maluma':** Ernst and Ernst (2011) suggest 'Maluma' is suitable for central leader training and high density planting because it is 'a less vigorous, precocious and productive early bearing Hass-like cultivar' with a 'natural central leader, with prominent lateral branching (≥ 90º angle)'. The sylleptic growth habit results in highly productive lateral branches.
- **'Nabal':** Barrett (1946) noted that 'Nabal' produced fruit on vertical limbs, 'unrelieved by laterals'. He recommended cutting back the tree at 3-4ft of the ground, just above three or four heavy laterals which are also shortened. These laterals then are allowed to 'bush' out under strict control, the shoots being shortened and thinned out at least every six months. No data was provided on the success of this strategy.
- **'Gem':** Mitchell (2019) reported that there has been interest in recent years in using 'Gem' for high density systems because it 'shows less vigour' and has an 'upright structure'.

Wolstenholme and Sheard (2012) provide a useful summary of the variable vigour of cultivars:

- Highly vigorous: 'Fuerte', 'Bacon', 'Sharwil', 'Zutano', 'Edranol', 'Ettinger'
- Moderately vigorous: 'Hass', 'Reed', 'Carmen', 'Harvest'
- Semi-dwarfed: 'Pinkerton', 'Lamb Hass', 'Shepard', 'Wurtz', 'Gwen', 'Gem', 'Maluma'

With the exception of Stassen *et al.* (1999b), there appear to be no published studies comparing the peformance of different cultivars. Stassen *et al.* (1999b) provided yield details of a trial of five cultivars at two spacings (using central leader shaping) (

Table 3). The authors also compared different pruning treatments: this is described in the section 'Comparative performance of canopy management ' on page - 34 -.

Table 3 Initial yields from five cultivars at different spacings from Stassen et al. (1999b)

Cultivar	Spacing (m)	Yield (Tonnes/ha) 1996	1997	1998	1999
	Months from planting	7	19	31	43
Fuerte	5.5 x 3	0	0	3.11 a	6.25 a
	4 x 1.5	0	0	3.39 a	5.33 b
Hass	5.5 x 3	0	0.50	4.87 a	9.34 a
	4 x 1.5	0	1.20	8.77 b	13.60 b
Pinkerton	5.5 x 3	0	0.67	7.03 a	8.07 a
	4 x 1.5	0	1.35	12.37 b	9.26 b
Edranol	5.5 x 3	0	0	6.06 a	17.2 a
	4 x 1.5	0	0	7.54 b	22.4 b
Ryan	5.5 x 3	0	0	4.96 a	11.9 a
	4 x 1.5	0	0	5.80 b	13.8 b

Means within the one column marked with the same letter are not significantly different at the 95% confidence level

As can be seen in Table 3, the higher density spacing with central leader shaping was less suitable for ‘Fuerte’ than for cultivars such as ‘Hass’ and ‘Edranol’. Some advice was provided on strategies for different cultivars.

- ‘Pinkerton’ and ‘Ryan’ with lower vigour do not have to be pruned as severely or as regularly as ‘Hass’ and ‘Fuerte’.
- With ‘Pinkerton’ a certain amount of new growth must be stimulated early in the season to carry the heavy crop on the trees. Not much shaping and pruning is done with this cultivar except for watershoot control where necessary.
- They considered ‘Edranol’ the ‘easiest’ of cultivars as its shoots develop evenly and well balanced, although this cultivar will reach its allotted height quickly and needs to be regularly controlled.
- ‘Ryan’ needs ‘opening up’ of the tree in autumn for better sunlight penetration. The new regrowth after this autumn pruning will also help sustain the following flowering and fruiting season (Stassen *et al.*, 1999b).

The authors provided data on the relative canopy growth of the five cultivars which illustrate these differences (Table 4).

Table 4 Increase in tree volume of five avocado cultivars at two different spacings over three seasons from Snijder and Stassen (1999b)

		Canopy volume (m^3)		
Cultivar	**Spacing (m) Months from planting**	**1996 7**	**1997 19**	**1998 31**
Fuerte	5.5 x 3	0.06	3.34	6.22
	4 x 1.5	0.05	2.54	5.99
Hass	5.5 x 3	0.03	2.68	6.63
	4 x 1.5	0.03	2.51	7.31
Pinkerton	5.5 x 3	0.01	1.58	2.34
	4 x 1.5	0.01	1.19	2.46
Edranol	5.5 x 3	0.01	1.56	5.42
	4 x 1.5	0.02	1.46	4.23
Ryan	5.5 x 3	0.02	1.71	3.86
	4 x 1.5	0.01	1.45	3.70

They recommend the following planting distances (for central leader shaped trees):

- 'Fuerte' 7 x 3.5m
- 'Hass' 6 x 3m
- 'Pinkerton' 5 x 2.5m
- 'Ryan' 5.5 x 3m
- 'Edranol' 5 x 2.5m

7. Canopy manipulation

There are many options for canopy manipulation, described below. Most orchardists will apply more than one strategy.

Early tree shaping

Several authors note the importance of initial shaping of trees in the nursery and when planted.

Some practical advice is provided as follows:

- France (1947) (for 'Fuerte') recommended cutting the tree to whips and a growing tip, then keeping the lower branches in control by pinching, with eventual removal of lower branches below a framework radiating from the trunk at least four feet from the ground. Branches that interfere with 'better' branches should be removed.
- Barrett (1946) (for 'Fuerte') recommended developing a strong vase-shaped head at 3-4 ft from the ground with three or four properly spaced leaders in the 2nd and 3rd years after planting. For this naturally spreading variety, Barret recommended pruning to encourage long, horizontal branches that are then allowed to 'build up' into smaller growth at the perimeter.

- Platt (1976) recommended regular pinching of growing tips for erect cultivars such as 'Bacon' and 'Zutano' to force lateral branching and prevent upward growth.
- For central leader shaping, Snijder and Stassen (1999b) recommended removing any branch that competes with the leader in the first year. Shoot complexity can be induced by tipping of shoots at 150 mm. They recommended establishing a branch hierarchy of well-spaced branches around the trunk. During the second year, the trees should be shaped and pruned continuously (tip, cut back or cut away branches) to maintain the branch hierarchy. Vigorous watershoots and any side shoots that compete with the leader should be removed. Shoots that are developing too closely together should be thinned to ensure light penetrates.

Stumping, stag-horning or top-working

Stumping and then stag-horning or top-working is an option for severely overcrowded orchards. There will be no crop for several years.

Hofshi *et al.* (2010) described the use of stumping and top-working trees to rejuvenate crowded orchards, producing a two-leader tree. The process in summary is:

- Undertake stumping and topworking in spring
- Topwork two shoots into the stumps with the same variety with grafting wood selected from known heavy producing trees in winter.
- Don't overwater after stumping.
- Remove regrowth from the stump regularly.
- Each season, girdle or cincture one of the leaders leaving a lateral branch below the girdle, to provide in due course a replacement leader.

The authors suggested that, if desired, new varieties can be interplanted at the same time. They will thrive as there is less competition for light.

Snijder and Stassen (1995) noted that staghorning strategies can fail if new growth is not managed. They suggested selecting 4-5 leader branches and maintaining upright growth on these. Other branches must be pruned to develop into bearing units with enough side branches for good yields close to the main framework. The authors say alternate rows can be staghorned., as long as the remaining trees are shaped to a pyramidal shape and size controlled, and the stag-horned trees are managed the moment new growth starts developing.

Hedgerow mechanical pruning

Hedgerow systems use trees planted more closely along the row than low density systems. They are mechanically pruned to form a 'wall' or 'hedge' along the row, usually at an angle of 15-20° to the vertical. Hedging research has established advice on appropriate conditions, time of hedging and shape of hedging cuts.

Mena (2005) and Hofshi (2004) described using hedgerows in plantings of 250 – 400 trees/ha with variable plant spacings but usually 6m rows.

Stassen (1999b) suggests sides should be pruned at 10° and tops at 25°. Pruning early in the season is followed by pruning late in summer to increase complexity. No data is given on success of this strategy.

Some researchers have experimented with timings. Adato in Israel, as reported in Hofshi (1996), aimed to encourage a prolonged summer flush by hedging early in spring. The later summer flush should not bloom and his hypothesis is that this later flush will contribute to the photosynthetic effort. He recommends the removal of later flushes to reduce flowering. Adato promotes application of a PGR at bloom to reduce fruit shoot competition. No data appears to be available to assess this approach.

Leonardi ran trials of various timings of post-harvest and summer hedging on 'Hass' in south-east Queensland and 'Shepard' in north Queensland (Leonardi, 2005; Leonardi *et al.*, 2005). Treatments were compared to unpruned controls. Some trials also looked at the effect of uniconazole (Sunny®) and procalcium hexadione (see section 'Plant growth regulators' on page - 28 -). Trees were hedged at 15° or 20°. Only two years were reported. Overall, hedging reduced yield in the first year by 39-56% compared to unpruned trees, with yields of pruned and unpruned trees being similar in the second and third year.

For the post-harvest pruning event, in southeast Queensland, Leonardi found that pruning 'Hass' immediately after harvest increased regrowth and the incidence of fruit body rots compared with unpruned trees. However, there was no significant effect of pruning two months after harvest on regrowth and body rots compared with unpruned trees. In north Queensland, pruning 'Shepard' immediately after harvest also increased regrowth and reduced yields. So, pruning 1-2 months after harvest was recommended for both scenarios.

For the summer pruning event, earlier timing (December) meant maximum shoot growth, but later timing (January and February) reduced flowering and yields. For example, at one site 55% and 43% of the shoots flowered in trees pruned in January and February respectively, compared with 88% in unpruned trees.

A study by Roe and Köhne in South Africa concluded hedging (with sides at 15° from upright) was more promising in a drier, less optimal growing environment, and less so in a warm moist environment. High rainfall resulted in 'almost uncontrollable growth' (yield data not actually provided) (Roe and Köhne, 1996)

Note that hedging is an unsuitable strategy for cool climate areas where fruit are on the tree for more than one growing season

Alternate row hedging

Whiley *et al.* (2013) recommend severe hedging of every second row in winter.

Alternate side hedging

An option is to hedge alternate sides each year e.g. Stassen (1999b), Snijder *et al.* (2000). Snijder *et al*. recommended hedging the eastern side first to prevent sunburn on the main branches at an angle of 10° and the treetops at 25° at the same time. In the second year, the eastern side will have developed new bearing shoots and tree height can be reduced as required. From the third year onward a lighter annual maintenance programme should be followed.

Hedging can be combined with window pruning (see section 'Window pruning' on page - 25 -)

Selective limb pruning

Selective pruning refers to the removal of some limbs and/or branches as distinct from 'hedging' or unselectively trimming the periphery of the canopy. The aim of selective pruning is to improve

light penetration into the midst of the canopy while managing tree size and height. Yield results are variable: the more severe the prune the more yields are adversely affected initially.

- Thorp and Stowell (2001) pruned 5-8m tall 8-year-old 'Hass' trees at 9 × 10-m spacing over three years at either 4 or 6 m in height by removing or heading back selected limbs. Yields were compared with those from control trees with no pruning. Reducing the number of main scaffold branches from 8-12 to 6-8 increased productivity of the remaining branches but cumulative yield over 3 years was similar to that of unpruned trees for the 6m height and lower for the 4m height. The authors suggested that improvements would continue with continued pruning. The height of the main fruiting zone was lowered on the 4-m trees, with yields in the 2-4-m zone similar to those in the 4-6-m zone of the control trees, thus possibly improving harvest efficiency. Fruit size increased on average.
- Snijder and Stassen describe their approach as follows: Treetops are made narrower by cutting back long branches so as not to overshadow the base and an open V-shape is obtained in the work-row. Angled branches that may cause overshadowing are removed and others cut to a more horizontal plane to produce strong side branches (Snijder and Stassen, 1995; Snijder and Stassen, 1999a; Snijder *et al.*, 2000; Stassen *et al.*, 1999a). Results varied with trial sites: either yield was not adversely affected (Snijder and Stassen, 1999a); was reduced in the first year and then improved (Stassen *et al.*, 1999a); or improved immediately (Stassen *et al.*, 1999a). This difference in results appears to be due to the severity of the prune as well as timing in terms of 'on' or 'off' years. Stassen *et al.* (1999a) noted that any strategy that applies only to one side of the tree or to alternate rows will be limited by the extent of overshadowing by the remaining tops of the trees or remaining rows.
- Francis (1994) of California recommended the following strategy for trees which begin to overcrowd even after trees are thinned: removal of two limbs per year, the tallest and the most lateral. After three years of this strategy, the trees should be under control and productive. No data on the success or otherwise of this strategy is provided.

Practical advice on pruning cuts

- Cutting *et al.* (1994) found that cuts below the bud ring (midway through the rhythmic growth flush) meant less bud break (i.e. new shoots) than cuts through the bud ring, although the shoots were a little longer. The average numbers were 0.73 and 7.8 buds breaking respectively; and 267.4mm and 241.5 mm growth respectively. Shoot growth was only slightly less vigorous when only one bud broke compared to growth when many buds broke.
- Avoid heading cuts particularly on the main or frame branches as encourages growth, particularly watershoot growth (no data) (Stassen *et al.*, 1995a)
- Always ensure that the branches are pruned back to other branches. Do not leave stumps, as these forms a bush of new growth, undoing the initial process of opening up the tree (Snijder and Stassen, 1997)

Practical advice on pruning after-care

- To reduce sunburn, Mena (2005) recommended painting of limbs exposed after pruning with white paint. Hofshi et al. (2010) also recommends this after stumping. Snijder *et al.* (2000) recommends painting limbs with a reflective paint.
- To reduce regrowth, Mena (2005) recommends painting top 30cm of pruned limbs with paint + Naphthalene acetic acid (NAA) (1% a.i.) (no supporting data given). Leonardi *et al.* (2005) found application of NAA to branches following pruning reduced regrowth in the treated area. However, regrowth occurred further down the branch. Whiley and Anderson (2002) in a study tour report comment on the effective application in California of NAA in killing shoots regrowing from stumps with either a 1% ethyl ester or sodium salt formulation of NAA in a 30% aqueous solution of a white acrylic paint. A 1% NAA formulation was applied to 'Reed' trees trained to central leaders that had been headed back and was reportedly effectively controlling shoot regrowth for up to 18 months following treatment. Hofshi et al. (2010) also recommends this after stumping if regrowth is an issue.
- Leal and Krezdorn (1977) tested the application of several growth regulators to terminal pruning wounds of small, container-grown avocado seedlings. The results showed that auxins, gibberellins and. cytokinins all stimulated callus formation and enhance wound healing. Auxins also consistently inhibited bud growth. GA, 2,4-D and benzyladenine at 200-400 p.p.m., 20-40 p.p.m. and 50-100 p.p.m., respectively, were the best treatments on the basis of callus formation, lack of phytotoxicity and bud growth near the wound area. However, application to trees in the field was unsuccessful, possibly because hot and dry conditions meant wounds could not be kept covered by either lanolin or water-based solutions.

Window pruning

Window pruning is a variation of selective pruning that aims to open up light gaps from the sides of the canopy rather than aiming to reduce height and reduce size. It can be combined with hedging to improve light infiltration into the canopy.

Work by Heath and Arpaia (2004) showed that light flecks need to be longer than 20-30 minutes to increase the photosynthetic activity of the leaf, suggesting any 'gaps' need to be substantial in size and well distributed.

Whiley *et al.* (2013) reported the use of combining hedging with 'window pruning' on an annual basis but no data is provided on the success of this strategy.

Tip pruning

Tip or shoot pruning is a strategy that may both reduce canopy size (although not drastically) and increase complexity. It is, of course, labour intensive.

Thorp and Sedgley (1993b) reported a range of strategies aimed at increasing structural complexity and subsequently fruit set. Shoot tipping successfully reduced the length of branches and increase axillary branching without affecting fruit set. They also trialled some plant growth regulators to increase complexity (see section Plant growth regulators for increasing complexity, page - 32 -).

Farré *et al.* (1987) outlined what they refer to as 'tip pruning' of 'Hass' trees in Malaga, Spain, comparing treatments of 'early' or 'late', 'heavy' or 'light' pruning, 'fruit thinning in late June' and an unpruned control. 'Early' was 2-8 March and 'late' was 18-30 March (the latter date was when flowers first appeared). While the authors state the light pruning involved removing summer growth and the heavy pruning both summer and spring growth, it is not clear how much was pruned, and in addition, not all trees were pruned every year. The 'early heavy' treatment produced the best yield, particularly in the off years. Overall, this report is not very enlightening.

Timing of pruning

The main objectives in timing pruning events are to minimise regrowth and at the same time allow floral shoots to develop fully before the next spring. It is generally agreed that this is best achieved by pruning after harvest/ in winter.

Several authors recommend pruning as soon as possible after harvest (Snijder and Stassen, 1997; Platt, 1976; Stassen, 1999b). Olesen (2005) found flowering was better from trees with earlier pruning dates i.e. closer to the winter solstice. Leonardi's work in southeast Queensland found hedging immediately after harvest exacerbated regrowth and was best delayed for 1-2 months (Leonardi *et al.*, 2005; Leonardi, 2005).

Köhne (1989) reported that pruning spring flushes (in 'Fuerte') resulted in rapid regrowth.

Cutting *et al.* (1994) compared growth from cutting shoots in late summer and late autumn and found the later date resulted in longer shoots (near Pietermaritzburg, in Natal in South Africa, "in the cool subtropical mist belt region").

Another aspect of timing pruning is to vary the intensity of pruning each year to help reduce biennial bearing. To that end, Snijder and Stassen (1997) recommend major pruning where an on-crop is expected.

Follow up/summer pruning

Several authors claim that the after harvest/winter prune is insufficient and further, usually lighter, pruning is required during the year.

The regular removal of watershoots or 'suckers' before they harden and removal of excessive vertical growth over summer is recommended by Snijder and Stassen in their publications (Stassen *et al.*, 1995a; Stassen and Snijder, 1996a; Stassen, 1999a; Snijder and Stassen, 1997; Snijder and Stassen, 1995; Snijder and Stassen, 1998; Snijder and Stassen, 1999a; Stassen *et al.*, 1999b; Snijder *et al.*, 2000). Snijder and Stassen (1995) said summer management of new shoots and suckers – done two to three times in each growing season -- is the 'second most important factor' after the initial pruning. They recommend three pruning events: post-harvest pruning, watershoot control in spring, and a 'light shaving' of shoot tips in in summer to induce complexity (Snijder and Stassen, 1999b; Stassen, 1999b; Snijder *et al.*, 2000)

Snijder and Stassen (1995) provide some interesting data to support this: they found that spring pruning improved 'light penetration' (no methodology is provided) at 1.5 m above ground from 7% (unpruned trees) to 58 %. However, by summer this had reduced to 11%. Management of shoots and suckers in summer increased this to 40%, and "with summer shaping" to 49% (not defined, but presumably pruning additional to removal of shoots and suckers).

Pruning side effects

A few 'side effects' to note: improving light penetration has been reported to increase the proportion of fruit lower in the tree, reducing picking costs. On the negative side, there may be some side effects on fruit quality and insect damage.

- Leonardi (2001) found pruning (hedging) treatments improved the proportion of fruit held at lower heights in the canopy(<2m) compared to the unpruned control. Thorp and Stowell (2001) also found the height of the main fruiting zone was lowered when trees were pruned to 4 metres compared to 6 metres.
- Leonardi *et al.* (2005) reported hedging treatments reduced calcium in fruit, which is associated with poorer fruit quality
- Oevering *et al.* (2005) later timing of pruning (i.e. April, rather than Jan to March in southern hemisphere) increased susceptibility to avocado thrips in the subsequent flush growth

Removal of dead wood

Removal of dead wood is recommended to reduce habitat for organisms that cause disease.

Everett *et al.* (2009) report that a one-off treatment of removal of dead wood from the canopy, combined with trimming the lower branches to a height of 1 m, reduced rots in fruit from one orchard but not another. The results in the latter orchard may be because the trees were much older (15-20 years compared to 5-6 years) and it was not possible to remove all the dead wood in one year. Other treatments such as calcium, irrigation and soil treatments had more beneficial effects. Barrett (1946) recommended removal of wood twice a year.

Rootstocks

Some rootstocks have been shown to reduce vigour to some extent, although the mechanisms are unclear. Reduced vigour may be associated with poorer root systems making trees more susceptible to *Phytophthora* and tree decline. Dwarfing rootstocks are not yet available.

Ben-Ya'acov *et al.* (1993) reported on the effect of rootstocks on tree size and productivity, concluding that dwarfing effects were more common from rootstocks in the West Indian race than other races. They report that the phenomenon of 'inverted bottle' was found in some but not all cases of dwarfing. This phenomenon is where the rootstock circumference is much smaller than the scion, possibly reflecting a smaller root system volume relative to canopy volume.

A central Queensland trial also found a strong influence of rootstocks on tree size (Le Lagadec, 2010). The trial included seedling and clonal rootstocks with both 'Hass' and 'Shepard' as scions. The seedling rootstock 'Ashdot' produced on average smaller trees and the highest yield efficiency (although with some signs of biennial bearing and stress by the end of the study), followed by 'BW2' and 'Degania'.

Hofman *et al.* (2021) reported that the height of 'Hass' trees on 'Ashdot' rootstocks in central Queensland was 86- 92% of trees on 'Velvick' rootstocks; and canopy volumes 82%- 86% of the trees on 'Velvick' rootstocks (varying with year)

The mechanism for reduced vigour from rootstocks is unclear. Thorp and Sedgley (1993b) found 'Hass' trees on the rootstock 'Velvick' had greater vigour with a higher ratio of sylleptic to proleptic shoots than trees on 'Hass' rootstock. Hofman *et al.* (2021) in central Queensland found that the proportion of branching that was sylleptic rather than proleptic was generally less for 'Hass' trees on 'Ashdot' than 'Velvick' rootstocks in most flushes but the difference between treatment means was only significant at one of the six measurement times. They concluded that a propensity to determinate flowering, and/or smaller root systems, contributed to the lesser growth of 'Hass' on 'Ashdot' rootstocks compared to 'Velvick' rootstocks.

Köhne and Schutte (1993) experimented with rings of bark in the rootstock below the graft union on 'Hass' trees: removing, reversing or substituting rings with bark from another cultivar. They found these treatments reduced the growth of the canopy, but the treatments reduced the health of trees or killed them.

Note that while many of the newer plantings in Peru and Chile are at higher densities, trees are mostly grafted on vigorous rootstocks such as 'Mexicola', 'Topa Topa', 'Degania' and 'Dusa®' (Newett, 2015b; Newett, 2015a).

Root pruning or root restriction

Root pruning and restriction are not options that have received much attention for avocado. Both positive and negative aspects are reported.

In an orchard which had been heavily pruned, Roe and Köhne (1996) reported they attempted root pruning to redress the root:shoot ratio. A trench 80 cm deep was dug around each tree at the drip line. They estimate around 90% of roots were cut. However, there were no evident positive or negative effects.

On the positive side, initial results reported by Winer (2007) showed root restriction improved irrigation efficiency and helped to control the growth of trees. This review could find no 'later' results. Gardiazabal and Mena (2011) suggest root competition in high density plantings in Chile helps reduce vigour, but no data is provided to support this.

On the negative side, Silber *et al.* (2012) compared trees grown in 100 and 200L lysimeters and found reduced growth (measured as trunk diameter) in the smaller containers, but also reduced yield. Whiley *et al.* (1999) found that root restriction in container grown avocado trees limited carbon assimilation.

Plant growth regulators for reducing vegetative growth

There are many studies in the literature that provide support for the use of plant growth regulators (PGRs) as a canopy management strategy, often in conjunction with pruning strategies. The main chemicals are the triazoles paclobutrazol (PBZ) and uniconazole (UCZ).

Triazoles

A range of studies show that triazoles can be used to reduce vegetative growth. They appear to increase yield by reducing competition between vegetative and reproductive growth in spring. Most trials have applied foliar treatments; less information is available about the effects of collar drenches or trunk injections. Application in spring has been more extensively studied than summer applications. The effects of summer applications appear to be less consistent.

Note some studies report yield effects but do not provide information on vegetative growth: these studies are in the main not included here.

Spring applications

There are many studies showing that applications in spring of PBZ or UCZ reduced shoot growth including Köhne and Kremer Köhne (1987), Köhne and Kremer Köhne (1989), Wolstenholme et al (1990; 1988), Adato (1990), Whiley *et al.* (1991), Leonardi (2005); Leonardi *et al.* (2005), Oosthuyse and Berrios (2015) and Symons and Wolstenholme (1990). Details of these studies can be seen in the box 'Studies on the use of triazoles to reduce shoot growth'.

Some authors suggest applications in heavy crop load years are superfluous or counterproductive e.g. Wolstenholme et al (1990; 1988) and Adato (1990).

Most authors applied foliar treatments: Oosthuyse and Berrios (2015) found drenches did not increase effectiveness but Köhne and Kremer-Köhne (1990a) found them more effective than foliar or stem injection methods. Chilean high-density systems reportedly use uniconazole applied through the irrigation at 4L per ha (Mitchell, 2019). In Australia, the use of soil drenches of the PGR 'AuStar®' (active ingredient paclobutrazol) for avocado trees less than 2.5m high is now permitted.

This chemical also reportedly encourages drooping or weeping branches rather than vertical growth, an added advantage in canopy management (Mitchell, 2019).

Timing

Timing of foliars at midbloom is recommended in most reports. However, (Mitchell, 2019), citing personal communications with Harley Smith (CSIRO) and Francisco Mena (GAMA Pty Ltd), that they believe applications later than mid bloom -- when spring flush is approximately 20cm long -- may be more useful. Data supporting this does not appear to have been published.

Summer carryover/summer applications

Wolstenholme et al (1990) found there was no carryover effect on summer flush of spring sprays of PBZ at 2.5 or 5 g of a.i. /litre.

On the other hand, Whiley *et al.* (1991) found mid-anthesis foliar treatment with PBZ reduced the length of summer shoots by ~ 20%, and one application rate (1.25 g a.i. L^{-1}) when combined with a trunk injection of PBZ at 0.2 g a.i. m^{-2} of canopy silhouette area when the spring growth matured, reduced the length of summer shoots by 36%.

Wolstenholme et al (1990) report that a summer spray of paclobutrazol at 2.5 g of a.i. had "a short-term effect on summer growth which was quickly outgrown (data not collected)" (p. 29).

Side effects

Growers using PGRs should be aware of reported side effects, including, potentially, increased fruit size (although results are equivocal), rounded fruit shape, and leaf distortion.

Wolstenholme *et. al.* (1990) reported individual fruit mass at harvest was increased by ~20% in the small-fruited 'Hass' from 2 x 2.5% sprays of PBZ but not from a single spray. In 'Fuerte', however, a lower fruit set on unsprayed trees meant fruit from unsprayed trees had greater mass. Whiley *et al.* (1991) found spray treatments of 2.5 and 1.25 g a.i. L^{-1} of PBZ at mid- anthesis increased the mean fruit size at harvest by 16 and 11% respectively. Symons and Wolstenholme (1990) also found fruit size increased. Erasmus and Brooks (1998) found fruit size for 'Fuerte' was unaffected by uniconazole ('Sunny®' at 1.0-1.5%); fruit size for 'Hass' increased.

Wolstenholme *et al.* (1990) reported fruit shape of both 'Hass' and 'Fuerte' was slightly less elongated. The average reduction in fruit length/diameter ratio was 6% in both cultivars. Erasmus and Brooks (1998) also reported rounder fruit, as did Symons and Wolstenholme (1990).

Higher concentrations in foliar sprays resulted in some leaf distortion ('bubbling') in work by Wolstenholme *et al.* (1990), which was quickly outgrown

In a trial with young avocado trees Bower and Cutting (1992) found trunk injections of paclobutrazol two to three weeks before the expected date of 50% flower opening (dosage not provided in this paper) increased polyphenol oxidase activity after ripening at 21° i.e. increased the potential for poor postharvest quality.

Studies on the use of triazoles to reduce shoot growth

- Köhne and Kremer Köhne (1987) applied foliar sprays of paclobutrazol (PBZ) at 0.4% ai or injections of 1mL at 1% ai dissolved in methanol to branches of 'Fuerte'/'Duke' trees. They found mean flush lengths on the apical indeterminate inflorescence of the branch for the spray, injection and control treatments were 40.1, 26.6 and 70.2mm respectively (P=0.05, the control treatment was significantly different from the other two treatments, which were not significantly different from each other at the 95% confidence level). Reduced growth was reportedly due to shortening of internodes. More fruit were retained on treated branches (graph but not data shown).
- Wolstenholme et al (1990; 1988) reported for 'Fuerte' and 'Hass' that foliar sprays of PBZ at .25 or .5% a.i. /L reduced spring flush shoot length by ~40% and reduced leaf area. Measurement of stem, leaf and fruit dry mass suggests that partitioning is affected in favour of fruit. Spring fruit set was increased but heavy summer fruit drop, however, nullified the latter effect in high yielding trees ('Fuerte', 19.0 t/ha, 'Hass', 29.3 t/ha). They suggest, therefore, that spring applications may be counterproductive in heavy cropping years. Overall tree size (over the nine months of the study) was unaffected by foliar sprays.
- Köhne and Kremer Köhne (1989) compared sprays of PBZ and UCZ in November on 70cm high potted seedlings at rates of 50, 100, 200, 400 and 4000 ppm ai and found all sprays reduced shoot extension with rates dependent on concentration. UCZ had greater effect.
- Adato (1990) sprayed 'Fuerte' trees with 2% Cultar® (= 0.8% PBZ) which reduced shoot length by ~30%, most effective when applied when inflorescences were elongating or anthesis was incipient i.e. somewhat earlier than other studies. Sprays increased yield except (as for Wolstenholme 1990) where crop loads were high. He attributes the increasing yield to an increase of 4-5 extra days in the gap between initial fruit set and the commencement of flush growth (thus reducing competition).
- Whiley *et al.* (1991) reported mid-anthesis foliar sprays of PBZ at 2.5, 1.25 and 0.62 g a.i. L^{-1} reduced spring growth in fruiting spring shoots of 'Hass'. The higher application rate increased starch concentration in the wood of spring shoots by ~ 70% compared to other treatments. There was a decrease in dry matter allocation to vegetative components and an increase in allocation to fruit. A combination of foliar spray and trunk application reduced the length of summer shoots by 36% when compared with untreated trees. Yield was not significantly affected by PBZ applications on an annual basis. However, the PBZ spray treatments of 1.25 and 0.62 g a.i. L^{-1} significantly increased the two-year cumulative yield by ca. 63%. There was no significant effect from the trunk injection treatment on fruit yield in either the season of treatment or the following season.
- Leonardi (Leonardi, 2005; Leonardi *et al.*, 2005) found that applications of UCZ (0.5 to 1% 'Sunny'®) applied to the post-harvest pruning increased fruit size 7-16% but not total yield. Applications to regrowth reduced shoot length for all timings. Summer applications also improved flowering compared to unsprayed treatments.
- Oosthuyse and Berrios (2015) compared spring PBZ sprays (Austar® at 1 or 2%) to untreated control trees, using three-year-old trees, cv 'Mendez'. Other treatments included addition of potassium nitrate (KNO_3) (2% w/v) to the sprays, or both addition of KNO_3 to sprays plus soil drenches of 3 or 6 mL Austar®. The PBZ reduced average shoot length of the spring flush from 35 to 23-24 cm for all treatments and increased mean fruit weight from 120g for the control to 171-183g for the other treatments. The additional use of drenches did not further reduce vigour. The addition of 2% (w/v) KNO_3 did not affect vigour but increased the number of fruits retained until harvest (0.57 to 0.75 fruits per inflorescence, or 32%).
- Symons and Wolstenholme (1990) (Natal) compared applications of three rates of PBZ at three times: early spring flush elongation, estimated full bloom and three weeks after full bloom. Only the last showed a significantly smaller increase in canopy area compared to the control (2.87m^2 compared to 5.87m^2). The authors posited that this may be because of the larger volume of young absorbent flush at the later date.
- Da Silva et al. (2015) reported for 'Hass' in Brazil (São Paulo State) that sprays of 0.7% Cultar® or 0.7 % Sunny® (0,035% uniconazole) shortened spring vegetative shoots (one year of data reported).

Studies on the use of triazoles to reduce shoot growth (continued)

- Köhne and Kremer-Köhne (1990a), found that of three application methods, foliar, stem injection or soil drenches of PBZ (to trees 1-2 years after planting) at 0.4g/m^2 of canopy profile, soil application was the most effective in reducing canopy size as measured by trunk diameter. It took 4-8 weeks for effects to show and the effect lasted 6-8 months. Yield results were variable. Stem injection (0.2g PBZ dissolved in methanol) proved to be phytotoxic.
- This rate of soil drench was applied to a high-density planting of 'Hass'/'Duke 7' (800 trees/ha) for three years with two drenches per year in the second and third years (Köhne and Kremer-Köhne, 1992). This approach reduced tree size compared to trees in a conventional spacing (400 trees/ha) planted at the same time. By year four the trees were crowding, and trees were thinned.

Prohexadione calcium

The plant growth regulator prohexadione-Ca is a gibberellin biosynthesis inhibitor. Relatively recent studies suggest limited effects on shoot growth and yield. Products such as this may have some use where use of triazoles is not permitted (e.g. the USA).

Prohexadione-Ca was tested on branches of 'Hass' shoots during bloom only over two consecutive seasons on 'Hass' in New Zealand (Mandemaker *et al.*, 2005). In the first year, flush growth was unaffected by a 1.4% ai application; in the second year, treatments with 1% ai seemed to slow growth later but differences in shoot length on average equated to <20mm on a 180-200 mm shoot. Numbers and size of fruit were unaffected.

Lovatt (2001) reported concentrations of 250mg/litre applied at the cauliflower stage of inflorescence development, anthesis and during fruit set *delayed* the elongation of the vegetative shoot and increased early fruit retention, but did not affect 'vegetative shoot growth' (which presumably means length) (only one year of results cited, no data presented).

Lovatt and Salazar-Garcia (2006) applied prohexadione calcium in mid-August after applications of GA in mid-July with the aim of stopping summer vegetative shoot growth and increasing floral development. This strategy did not seem to work as yield was not increased, although mean fruit size *did* increase. No data was provided on shoot growth.

Leonardi *et al.* (2005) found that prohexadione calcium ('Apogee' at1.25 g/L) when applied at mid-bloom to 'Hass' reduced the incidence of body rots with 12% of the fruit affected compared with 25 % in untreated trees. No data on effects on shoot growth were provided.

Chlormequat chloride

Stassen *et al.* (1999b) experimented with Cycocel® (750 g.L^{-1} chlormequat chloride) at 0.4% applied once at full flower, or at full flower and again on the summer flush when it was 150-200 mm in length applied to 4-year-old 'Hass'. These treatments were compared to treatments of Cultar® (250 g.L^{-1} paclobutrazol) at 0.4%/0/4% and Sunny® (50 g.L^{-1} uniconazole) at 0.7%/0.3% on the same two dates, and an untreated control. Treatments were applied to a pruned orchard at 2.5 x 5 m spacings. There were no significant differences between the various treatments in yield except where Cultar® was sprayed twice (this improved yield). There was a non-significant improvement in yield for the single (at flowering) spray of Cultar® and the two Sunny® sprays. The Cycocel® treatments did not improve yield. No data on effects of vegetative growth were given.

Plant growth regulators for increasing complexity

The product 'Cytolin' ® has been tested for increasing complexity. It was found to increase axillary branching but also shoot extension.

'Cytolin' (® Sumitomo Chemicals, 19g/L 6-benzyladenine and 19g/L gibberellins $_{4+7}$) is a plant growth regulator that has been used successfully in several tree crops to increase sylleptic branching.

Thorp and Sedgley (1993b) found, when spraying individual shoots of 'Hass' in New Zealand, that 'Cytolin' applications applied in late spring to shoots that had just completed shoot extension increased shoot length and sylleptic axillary shoot growth and subsequent fruit set. The auxin inhibitor TIBA (2,3,5-triiodobenzoic acid) stimulated proleptic axillary shoot growth without effect on fruit set.

Hofman *et al.* (2021) tested the use of 'Cytolin' applied at the end of extension of the spring flush to increase sylleptic axillary shoot branching over three years. They reported that the 'Cytolin' spray treatments induced some increase in branching but also induced an unwelcome length of growth in the subsequent flush, and that this growth may have reduced growth in subsequent flushes. Gains in sylleptic branching did not translate into any discernible increase in yield.

Girdling

Branch girdling or ringing (removal of a strip of bark) is generally viewed as a strategy for increasing flowering and yield (not reviewed here) rather than as a canopy management strategy. It has been used as a strategy for temporarily increasing yield before tree removal. However, it is also reported as a strategy to reduce vigour and in conjunction with branch removal.

Branch girdling is reported as a strategy for temporarily increasing yield before tree removal (Toerien and Basson, 1979b). However, there are also some reported uses of it as a canopy management strategy or to reduce vigour as follows:

Mitchell (2019) notes that growers in California use girdling to promote flowering in water shoots which are removed after the following harvest. He notes this is important strategy in California in the absence of PGRs.

Köhne and Schutte (1993) used girdling to reduce the growth rate of young 'Hass' trees. While tree size was controlled, the condition of treated trees deteriorated, possibly because the girdle was too wide.

Snijder and Stassen (1999b) recommend girdling of branches on young trees (second year onwards) if growth is vigorous. This should be done late in the growing season (February-March).

Kaluski in Israel, described in Hofshi (1996), promoted a system of branch removal, girdling, frequent pruning, and tree manipulation to achieve a constantly rejuvenated tree with the oldest branch not older than two to three years. The goal was to restructure the tree in three years, lowering the canopy to four metres. Each year one branch was removed, and two branches girdled: one in autumn and one in spring. The purpose of girdling is to minimize alternate bearing. Plant growth regulators are applied at peak bloom and at the end of bloom.

Ground cover

Maintaining enough light to support interrow groundcover is an objective in canopy management systems.

Atucha *et al.* (2013) compared groundcover management systems on a hillside planting in a three-year study: bare soil, a vegetation strip and groundcover over the entire plot surface. Trees in the bare soil plots were 44 and 53 % bigger, and had 150 and 250 % higher yields, than trees in the vegetation strip and total groundcover plots respectively. However, runoff volumes and soil volumes were higher and carbon soil nitrogen lower.

Water and nitrogen management

While a full exploration is outside the scope of this review, nutrient management is a factor in growth and authors such as Chartzoulakis *et al.* (2002) Stassen (1999b) and Snijder *et al.* (2000) comment on the need for judicious nitrogen and irrigation management to avoid excessive growth.

8. New technologies to aid in decision making

Research into technologies which aid in canopy assessment and pruning decisions are now emerging in the literature.

Wu *et al.* (2018) report on using a light detection and ranging (LiDAR) system from a Terrestrial Laser Scanning (TLS) system to assess leaf area and vertical leaf area profiles for mango, macadamia and avocado trees: as assessment of growth using these tools could be used in decisions of which trees or parts of the orchards need to be pruned. Westling *et al.* (2021) present a framework for suggesting pruning strategies on LiDAR-scanned commercial fruit trees using a scoring function to assess tree shape with a focus on improving light distribution throughout the canopy. The scoring function rates total light absorbed while penalising leafy matter with access to < 25% full sun. The scoring function was 'reasonably' correlated with yield of avocado (r^2 of 0.615). A tool for simulating pruning was developed to estimate which parts of the tree canopy would be removed given specific cut points. Finally, new pruning points were suggested by discovering points in the tree which negatively impact the light distribution. Light distribution was improved by up to 25.15%, demonstrating a 16% improvement over the commercial pruning, and certain cut points were discovered which improved light distribution with a smaller negative impact on tree volume. This framework could be used as a decision-making tool by growers, or as a starting point for automated pruning.

At a more macro level, Robson *et al.* (2014); (2017) reported using satellite imagery, Geographical Information Systems (GIS) and Google Earth for tree auditing and for defining the spatial variability of tree condition. While this seems less directly relevant to canopy management than the two studies noted above, such tools may help define areas of the orchard that need more attention.

9. Comparative performance of canopy management approaches

There are some studies which provide comparative data on different planting and/or canopy manipulation systems, but together these do not add up to a clear picture of the most effective options. Possibly selective pruning has the edge on mechanical pruning; and low density on high density plantings, but these conclusions are at best tentative and depend on circumstances.

The studies are summarised below:

- Köhne and Kremer-Köhne (1990b) compared 'Hass' on 'Duke 7' rootstock planted at a standard spacing of 5.0 x 5.0 m (400 trees/ha), and at high density spacings of 2.5 x 5.0 m (hedge) and 5.0 x 2.5 m (bed) (800 trees/ha). The bed consisted of three rows together without a laneway in between them (see Figure 3 below).

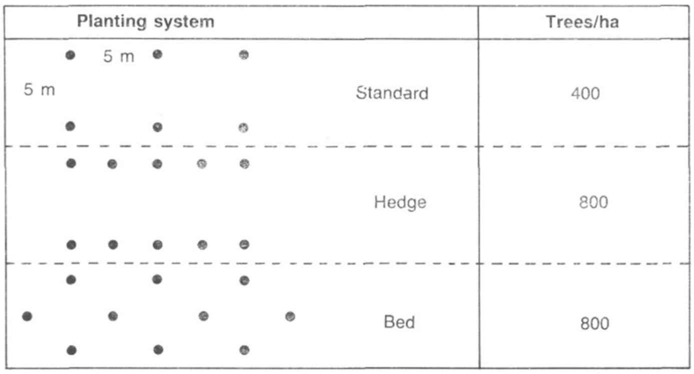

Figure 3. Planting systems of Hass trees on Duke 7 rootstock

Paclobutrazol treatments (foliar, stem injection *and* soil drenches) were part of the two higher density systems but not the lower density. The paclobutrazol reduced growth as measured by trunk circumference. The best yield efficiency and the highest production/ha in the two reporting years were from paclobutrazol-treated trees in the high-density beds.

- Hofman *et al.* (2021) reported on comparisons of low-density plantings (9x5m) of 'Hass' in central Queensland (with minimal pruning until the fourth year when selective pruning was applied), with medium (6 x 3m) and high-density trellised plantings (4.5 x2m). Both medium and high densities had regular selective pruning to maintain a central leader shape. Yield per hectare was highest from the low density minimally pruned trees in the reported years (Table 5). The authors demonstrated that this was not just a matter of canopy volume: the high and medium density treatments had lower yield efficiencies (kg of fruit per m^3 of canopy volume). Note that canopy volume calculations did not take into account gaps in the canopy. The authors demonstrated that the higher densities had somewhat poorer canopy complexity and consistency, particularly loss of lower branches, but on a per hectare basis, the number of flowering terminals was higher for the higher densities, so this was not the major factor in depressing yields. The problem was demonstrably due to lower percentages of fruit set and retention. This poorer fruit set was attributed to lower canopy efficiency, low root system efficiency and higher fruit-shoot competition.

Table 5 Yield (tonnes/ha) of 'Hass' on two rootstocks by density/shaping/pruning treatments 2015/16 to 2018/19 from Hofman et al. (2021)

Density/shaping/pruning treatment	**2015/16**	**2016/17**	**2017/18**	**2018/19**
High density/ central leader/ selective pruning	7.33 b	8.9	12.28	11.3 a
Medium density/ central leader/ selective pruning	1.85 a	8.2	13.38	16.0 b
Low density/no shaping/no pruning until selective pruning in 2018/19	1.71 a	6.6	13.37	19.6 b
P	*<.001*	*0.314*	*0.696*	*0.004*
ese	*0.73*	*1.0*	*1.0*	*1.2*

Means in a row that are marked with the same letter are not significantly different at the 95% confidence level

- Stassen *et al.* (1999a) provides one year of yield data on a trial of various pruning strategies in an overcrowded orchard of 12-year-old trees that had previously yielded 21.0, 23.7, and 14.9 tonnes/ha in successive years. The most successful strategy was selective pruning of treetops, although this was not significantly different from some other strategies at the 95% confidence level. The strategies followed by mean yields in tonnes/ha were:
  - Selective pruning of the whole tree 19.9 a
  - Selective pruning of tree tops 25.4 a
  - Mechanical pruning of one side 20.2 a
  - Mechanical pruning of both sides 10.7 b
  - Standard pruning (open up work rows) 11.5 b

  (Means with the same letter as suffix are not significantly different at P≤0.05 using the Tukey test.)

Stassen *et al.* (1999b) compared selective pruning with mechanical hedging on a range of cultivars planted at 5.5 x 3 m or 4 x 1.5m. Results varied with cultivar and spacing (

- Table 6). In the 4 x 1.5 m spacing, 'Hass', 'Fuerte' and 'Edranol' produced significantly higher yields when only selective pruning was applied. Selectively pruned 'Pinkerton' on the other hand produced significantly less than the mechanically pruned trees at the 4 x 1.5 m spacing. At the 5.5 x 3 m spacing for 'Fuerte' there was lower yield where mechanical pruning applied in the post-harvest period was followed up by selective pruning in the summer period. For 'Pinkerton' and 'Edranol' at the wider spacing there was no significant difference between the three pruning treatments.

Table 6 Initial yields from three different pruning treatments from Stassen et al. (1999b)

Cultivar	Spacing (m)	Yield (tonnes/ha) Selective pruning both PH and summer	Combined selective (PH)→mechanical (summer)	Combined mechanical (PH)→selective (summer)
Hass	5.5 x 3	9.3 a	7.7 ab	5.8 b
	4 x 1.5	13.7 a	8.5 b	7.0 b
Fuerte	5.5 x 3	6.2 a	6.2 a	2.8 b
	4 x 1.5	5.3 a	1.8 b	1.0 b
Pinkerton	5.5 x 3	8.1 a	7.5 a	7.0 a
	4 x 1.5	9.3 b	13.0 ab	15.0 a
Edranol	5.5 x 3	17.2 a	15.1 a	14.3 a
	4 x 1.5	22.4 a	9.8 b	13.2 b

PH= postharvest; Means in a row that are marked with the same letter are not significantly different at the 95% confidence level

- Stassen *et al.* (1999b) compared a 5 x 2.5 m central leader planting with an unpruned 5 x 5 m planting. The higher density planting did not give significantly higher yields in the three reporting years (3, 4 and 5 years after planting). The authors muse that this may have been due to high N reserves in the soil which prompted 'tremendous' growth which required 'drastic' pruning.
- Bender and Faber (2001) compared yield results from eight pruning styles in California:
  - Stumped, pruned to Cal Poly style (vase shape). Trees were topped at 14 feet in height
  - Stumped at three feet height, pruned to a single leader. Trees were topped at 14 feet in height.
  - Stumped, no follow up pruning.
  - 'High' stumped at eight feet height, pruned to Cal Poly style.
  - Two cut pruning. Each year one of the worst encroaching branches (into a neighbouring tree) is removed and one branch high in the tree (above 15 feet) was removed. The aim is to bring the height of the tree down and the canopy width in closer to the trunk.
  - 'Israeli method', one main branch removal per year.
  - Thinning. Every other tree (on a diagonal pattern) was removed in the first year. Remaining trees were allowed to grow into the space of the removed trees without pruning.
  - Unpruned control.

Results for Year 3 are shown in

Table 7 (no further data is available as this trial was abandoned after a ‘freeze’, pers. comm. B. Faber 2 March 2022). On a lb/acre basis, the ‘control’ and ‘thinned’ styles yielded most, followed closely by the ‘Israeli’ method. The authors think the high rates from the control block may be due placement of beehives (note trial design appears to be unreplicated single blocks for each treatment), an advantage not shared by the ‘thinned’ and the ‘Israeli’ treatments which also yielded well.

Table 7 Yield from eight pruning styles without border trees (Stehly Ranch, Valley Centre) from Bender and Faber (2001)

	Lb/tree	Lb/acre	Lb/fruit	Picking cost/lb	N (no. of data trees)
Control	233.8	24,401	0.40	$0.23	4
CalPoly	36.7	3,998	0.55	$0.07	4
Single leader	49.5	5,391	0.58	$0.07	4
Stumped, no follow-up	111.3	12,134	0.52	$0.07	4
Thinned	447.6	24,616	0.40	$0.06	2
Two cut	160.6	14,234	0.45	$0.15	4
Israeli	188.5	20,542	0.40	$0.07	4
High stumped, CalPoly	5.2	570	0.50	$0.03	4

Definitions and abbreviations

biennial bearing	tendency for a tree to produce a greater than average crop one year, and a lower-than-average crop the following year
bu	bushels. A bushel is a volume measure equivalent to 36.4 litres
CO_2	carbon dioxide
determinate	refers to inflorescences that do not produce a vegetative growth unit from their apex. Compare *indeterminate*
GA	gibberellic acid, a regulator of plant growth and development with many roles, including promotion of growth through cell elongation and activation of various developmental stages, including vegetative and reproductive development. There are many forms of gibberellins: 3, 4 and 7 are the most commonly used in exogenous plant growth regulators.
growth unit	the section of a branch that grows in a single flush
indeterminate	refers to inflorescences that produce a vegetative growth unit from their apex. Compare *determinate*
Lb	pounds
µmol m-2 s-1	Micromole per second and square meter. this term is based on the number of photons in a certain waveband incident per unit time (s) on a unit area (m2) divided by the Avogadro constant (6.022 x 1023 mol-1). It is used commonly to describe PAR in the 400-700 nm waveband.
'on' and 'off' years	refers to heavy and light crop loads (respectively) in a biennial bearing pattern
P or *P* value	the 'probability value' describes how likely it is that the data would have occurred by random chance because of the variability in the population. A P value of less than 0.05 is used as the standard for declaring that treatment means are significantly different.
PAR	photosynthetically active radiation, that is, the wavelengths of light that are used in photosynthesis (400-700 nm)
PBZ	paclobutrazol
PPFD	photosynthetic photon flux density; this considers only light in the waveband from 400 nm to 700 nm.
proleptic	refers to the time of growth of the first growth unit of a branch: growth is in a later flush than the parent growth unit i.e. after a 'resting' period. Compare *sylleptic*
sylleptic	refers to the time of growth of the first growth unit of a branch: growth occurs in the same flush as the parent growth unit. Compare *proleptic*
UCZ	uniconazole

References

Adato, I. (1990). Effects of paclobutrazol on avocado (*Persea americana* Mill.) cv. Fuerte. *Scientia Horticulturae* 45: 105-115.

Aounallah, M. K., Hammami, S. B. M., Farah, R., Sahli, A. & Bettaieb, T. (2017).Flower development and timing of avocado (*Persea americana*) growing under Tunisian conditions. In *Acta Horticulturae*, Vol. 1160, 397-402 (Ed E. Costes). International Society for Horticultural Science.

Atucha, A., Merwin, I. A., Brown, M. G., Gardiazabal, F., Mena, F., Adriazola, C. & Lehmann, J. (2013). Soil erosion, runoff and nutrient losses in an avocado (*Persea americana* Mill) hillside orchard under different groundcover management systems. *Plant and Soil* 368(1-2): 393-406.

Averett, W. E. (1949). Tree thinning the avocado grove by the block system. *California Avocado Society Yearbook* 34: 110-117 pp.

Barrett, C. (1946). Planting and pruning avocado trees. *California Avocado Society Yearbook* 30: 116-119.

Ben-Ya'acov, A., Michelson, E. & Sela, I. (1993). Rootstock effect on avocado vigor and productivity. *Acta Hortic.* 349: 191-195.

Bender, G. & Faber, B. A. (2001).Report on avocado pruning trials (Continuing Project, Year 3 of 5). 105-108: University of California Cooperative Extension, San Diego and Ventura Counties

Biran, D. (1979).MSc thesis: Fruitlet abscission and spring growth retardation-- their influence on avocado productivity. Vol. MScIsrael: The Hebrew University of Jerusalem.

Bower, J. P. & Cutting, J. G. M. (1992). The effect of selective pruning on yield and fruit quality in 'Hass' avocado. *Acta Horticulturae* (No. 296): 55-58.

Chartzoulakis, K., Patakas, A., Kofidis, G., Bosabalidis, A. & Nastou, A. (2002). Water stress affects leaf anatomy, gas exchange, water relations and growth of two avocado cultivars. *Scientia Horticulturae* 95(1-2): 39-50.

Chirachint, W. & Turner, D. W. (1988). Shade reduces the foliar symptoms of 'Fuerte' avocado affected by salt, without significantly changing the concentration of Na, K or Cl in the leaves. *Scientia Horticulturae* 36 1-15.

Crane, J. H., Schaffer, B., Davenport, T. L. & Balerdi, C. (1992). Rejuvenation of a mature, non-productive 'Lula' and 'Booth 8' avocado grove by topping and tree removal. *Proceedings of the Florida State Horticultural Society* 105: 282-285.

Cutting, J. G. M. (2003). Research note: Impact of spring and summer flush type on flowering intensity in 'Hass' avocado. *New Zealand Avocado Growers' Association Annual Research Report* 3: 42-47.

Cutting, J. G. M. & Bower, J. P. (1990). Spring vegetative flush removal: the effect on yield, size, fruit mineral composition and quality. *South African Avocado Growers' Association Yearbook* 13: 33-34.

Cutting, J. G. M., Cocker, B. & Wolstenholme, B. N. (1994). Time and type of pruning cut affect shoot growth in avocado (*Persea americana*) Mill. *Journal of Horticultural Science* 69(1): 75-80.

Da Silva, S. R., Cantuarias-Aviles, T., Brogio, B. A., Angolini, S. F. & Cagale, L. I. (2015).Plant growth regulators for 'Hass' avocado production under rain-fed conditions in Brazil (abstract). In *Proceedings of the VIII World Avocado Congress*Lima, Peru.

Dixon, J. (2007). Shoot growth of 'Hass' avocado trees in 'on' and 'off' flowering years in the western Bay of Plenty. *New Zealand Avocado Growers' Association Annual Research Report* 7: 41-48.

Dixon, J., Elmsley, T. A. & Greenwood, A. C. (2007). Differences in initial fruit set on determinate and indeterminate flowering shoots. *New Zealand Avocado Growers' Association Annual Research Report* 7: 31-40.

Erasmus, H. D. & Brooks, W. H. (1998). Foliar application of uniconazole (Sunny) to avocado trees to improve fruit size and yield and to change fruit shape. *South African Avocado Growers' Association Yearbook* 21: 52-53.

Ernst, Z. R. & Ernst, A. A. (2011).High density cultivation: a case study of central leader pruning with Maluma. In *Proceedings of the VII World Avocado Congress* Cairns, Australia.

Evans, L. J., Goodwin, R. M. & McBrydie, H. M. (2010). Factors affecting 'Hass' avocado (*Persea americana*) fruit set in New Zealand. *New Zealand Plant Protection* 63: 214-218.

Everett, K. R., Boyd, L. M., Pak, H. A. & Cutting, J. G. M. (2007). Calcium, fungicide sprays and canopy density influence postharvest rots of avocado. *Australasian Plant Pathology* 36(1): 22-31.

Everett, K. R., Pushparajah, I. P. S., Timudo-Torrevilla, O. E. & Manning, M. A. (2009). Orchard treatments other than spray application of fungicides that reduce postharvest rots of avocados *New Zealand Avocado Growers' Association Annual Research Report* 8: 93-98.

Farré, J. M., Hermoso, J. M. & Pliego, F. (1987). Effects of pre-bloom pruning on leaf nutrient status, growth and cropping of the avocado cv. Hass. *South African Avocado Growers' Association Yearbook* 10: 71-72.

France, J. G. (1947). Practical points in avocado pruning. *Yearbook of the California Avocado Society* 31: 89-91.

Francis, H. L. (1971). Evaluation of an avocado orchard thinning program *California Avocado Society Yearbook* 54: 21-23.

Francis, H. L. (1994). What to do with tall, crowding trees in orchards previously thinned *California Avocado Society Yearbook* 78.

Gardiazabal, F. J. & Mena, F. (2011). The avocado industry in Chile and its evolution. *California Avocado Society Yearbook* 94: 52-68.

Givnish, T. (1988). Adaptation to Sun and Shade: a Whole-Plant Perspective. *Functional Plant Biology* 15(2): 63-92.

Hadari, M. (2004).A three-dimensional model of the light regime in an avocado orchard. In *Water, Soil and Environmental Engineering*, Vol. Master of Science of Agricultural Engineering Haifa: Israel Institute of Technology

Hall, H. (2015).Final Report Australian Avocado Industry Benchmarking Program (Project no. AV13003). Sydney: Pinnacle Agribusiness.

Heath, R. L. & Arpaia, M. L. (2004).Avocado tree physiology - understanding the basis of productivity (New Project: Year 3 of 5). In *Proceedings of the California Avocado Research Symposium*Riverside: University of California, Riverside.

Hofman, H., Wilkie, J., Griffin, J., Parfitt, C. & Toegel, H. (2021).Appendix 2 Avocado Planting Systems Trial 2014-2019, in Transforming tropical/subtropical tree productivity: Final report (project AI13004). Hort Innovation.

Hofman, H., Wilkie, J. D., Griffin, J. & Langenbaker, R. (2018). Efforts to understand and improve crop load of 'Hass' avocado. *Acta Horticulturae* (No.1228): 331-338.

Hofshi, R. (1996). Accepted and perceived limiting factors to avocado production in Israel - solutions and setbacks *California Avocado Society Yearbook* 80:.

Hofshi, R. (1999).Some economic reasons to consider canopy management In *Proceedings of Avocado Brainstorming*, 45-48 (Ed M. L. A. a. R. Hofshi). Riverside, CA.: Hofshi Foundation.

Hofshi, R. (2004).Beyond yield: re-engineering the avocado. In *2nd Seminario Internacional de Paltos*Quillota, Chile: Sociedad Gardiazabal y Magdahl Ltda.

Hofshi, R., Tapia, M. & Arpaia, M. L. (2010). Stump and topwork -- a technique for rejuvenating mature avocado trees. *California Avocado Society Yearbook* 93: 51-71.

Köhne, J. S. & Kremer-Köhne, S. (1987). Vegetative growth and fruit retention in avocado as affected by a new plant growth regulator (Paclobutrazol). *South African Avocado Growers' Association Yearbook* 10: 64-66.

Köhne, J. S. & Kremer-Köhne, S. (1989). Comparison of growth regulators paclobutrazol and uniconazole on avocado. *South African Avocado Growers' Association Yearbook* 12: 38-39.

Köhne, J. S. & Kremer-Köhne, S. (1990a).Effect of paclobutrazol on growth, yield and fruit quality of avocado in a high density orchard. In *Acta Horticulturae*, Vol. 275, 199-204: International Society for Horticultural Science (ISHS), Leuven, Belgium.

Köhne, J. S. & Kremer-Köhne, S. (1990b). Results of a high density avocado planting. *South African Avocado Growers' Association Yearbook* 13: 31-32.

Köhne, J. S. & Kremer-Köhne, S. (1992).Yield advantages and control of vegetative growth in a high-density avocado orchard treated with paclobutrazol. In *Proc. of Second World Avocado Congress*, 233-235.

Köhne, J. S. & Schutte, J. M. (1993). Progress report on avocado tree size control by means of bark manipulation, dwarfing interstocks and rootstocks. *South African Avocado Growers' Association Yearbook* 16: 18-19.

Köhne, S. (1989).Spring growth of avocado trees as influenced by pruning and the use of growth regulators to stabilise yield and improve fruit quality. In *Faculty III Agricultural Sciences I*, Vol. Doctor of Agricultural Science: University of Hohenheim.

Le Lagadec, D. (2010).Final report AV07008: Field evaluation of superior avocado rootstocks with ‘Hass’ and ‘Shepard’ as scions. Bundaberg: Horticulture & Forestry Sciences, Agri-Science Queensland, Department of Employment, Economic Development and Innovation (DEEDI)

Leal, A. T. & Krezdorn, A. H. (1977). Effects of growth regulators on healing avocado pruning wounds. *Proceedings of the Florida State Horticultural Society* 90: 275-278.

Leonardi, J. (2001). Progress in canopy management of avocados. 18?

Leonardi, J. (2005).New strategies and tools for avocado canopy management. In *New Zealand and Australia Avocado Growers' Conference*Tauranga, New Zealand.

Leonardi, J., Hofman, P., Menzel, C. M. & Stubbings, B. (2005).Project no AV00007 Final report: Avocado canopy and orchard floor management. Sydney: Department of Primary Industries and Horticulture Australia Ltd.

Liu, X., Mickelbart, M. V., Robinson, P. W., Hofshi, R. & Arpaia, M. L. (2002).Photosynthetic characteristics of avocado leaves. In *Acta Horticulturae*, Vol. 575, 865-874: International Society for Horticultural Science.

Lovatt, C. J. (2001).Developments in plant growth regulators: manipulation of vegetative growth, flowering and fruiting of avocados. In *Australian and New Zealand Avocado Growers Conference*Bundaberg, Queensland.

Lovatt, C. J. & Salazar-Garcia, S. (2006).Plant growth regulators for avocado production. In *Proceedings of the 33rd Annual Meeting of the Plant Growth Regulation Society of America*, 98-108 Quebec City, Canada.

Mandemaker, A. J., Cutting, B. T., Smith, D. B. & Dixon, J. (2005). Effect of prohexadione-Ca on shoot growth, fruit set and retention in 'Hass' avocado in New Zealand. *New Zealand Avocado Growers' Association Annual Research Report* 5: 35-42.

Marsh, R. H. (1941). Thinning crowded avocado orchards. *California Avocado Society Yearbook* 26: 58-59 pp.

Martin, G. & Witney, G. W. (1995). Avocado tree structuring. *Proceedings of the World Avocado Congress*: 245-250.

Mena, F. (2005).Growing avocados in Chile: A focus on orchard systems, fruit set and size. In *New Zealand and Australia Avocado Grower’s Conference* Taurandga, New Zealand.

Menzel, C. M. & Le Lagadec, M. D. (2014). Increasing the productivity of avocado orchards using high-density plantings: A review. *Scientia Horticulturae* 177: 21-36.

Mickelbart, M. V., Larsen, S., Heath, R. & Arpaia, M. L. (2007). Changes in photosynthesis during flush development in avocado (*Persea americana* mill.)(abstract). *HortScience* 42(4): 992-992.

Mickelbart, M. V., Robinson, P. W., Witney, G. W. & Arpaia, M. L. (2012). ‘Hass’ avocado tree growth on four rootstocks in California. II. Shoot and root growth. *Scientia Horticulturae* 143: 205–210.

Mitchell, D. (2019).High density avocado production: Constructing an integrated management tool (Nuffield Australia Project No. 1809) North Sydney: Nuffield Australia.

Newett, S. (2015a).Report on avocado orchard visits in Peru, September 2015. Vol. http://bestpractice.avocado.org.au> Growing > South American orchard visits, Last modified 11 Ocober 2016, accessed 2012 December 2016: Avocados Australia.

Newett, S. (2015b).Report on visit to avocado orchards in Chile, September 2015. Vol. http://bestpractice.avocado.org.au > Growing > South American orchard visits, Last modified 11 October 2016, Accessed 2012 December 2016: Avocados Australia.

Oevering, P. E., Faber, B. A. & Phillips, P. (2005). Time of avocado pruning affects fruit set and avocado thrips occurrence in Southern California groves. *California Avocado Society Yearbook* 87: 83-96

Olesen, T. (2005). The timing of flush development affects the flowering of avocado (*Persea americana*) and macadamia (*Macadamia integrifolia* * tetraphylla). *Australian Journal of Agricultural Research* 56(7): 723-729.

Oosthuyse, S. A. & Berrios, M. (2015).Increased fruit retention and size and reduced new shoot vigour in Mendez avocado resulting from spray application of paclobutrazol plus potassium nitrate during flowering. In *VIII World Avocado Congress*, 362-365 Lima, Peru.

Osmond, B., Förster, B. & Leonardi, J. (2011).Photoprotection in avocado leaves in relation to canopy management (Powerpoint slides of presentation). In *Proceedings of the VII World Avocado Congress*Cairns, Australia.

Platt, R. G. (1976).Tree spacing and control of avocado tree growth. In *Proceedings of the First International Tropical Fruit Short Course: The Avocado.*, 54-57. Gainesville: Fruit Crops Dept., Florida Cooperative Extension Service. Institute of Food and Agricultural Sciences, University of Florida.

Razeto, B., Fichet, T. & Longuiera, J. (1995).Close planting of avocado. In *Third World Avocado Conference*, 227-232 Israel.

Razeto, B., Longuiera, J. & Fichet, T. (1992).Close planting of avocado. In *Proceedings of the II World Avocado Congress*, 273-279 Orange, California.

Robson, A., Moshiur Rahman, M. & Muir, J. (2017). Using worldview satellite imagery to map yield in avocado (*Persea americana*): a case study in Bundaberg, Australia. *Remote Sensing* 9.

Robson, A., Petty, Joyce, D., Hofman, P. J. & Marques, R. (2014).High resolution remote sensing, GIS and Google Earth for avocado fruit quality mapping and tree number auditing. In *International Conference for Horticultural Science*Brisbane.

Roe, D. J. & Köhne, J. S. (1996). Root pruning and hedgerowing of avocado trees at Westfalia Estate: What have we learnt? *South African Avocado Growers' Association Yearbook* 19: 61-62.

Salazar-Garcia, S. & Lovatt, C. J. (1998). GA_3 application alters flowering phenology of 'Hass' avocado. *Journal of the American Society for Horticultural Science* 123(5): 791-797.

Scholefield, P. B., Walcott, J. J., Kriedemann, P. E. & Ramadasan, A. (1980). Some environmental effects on photosynthesis and water relations of avocado leaves. *California Avocado Society Yearbook* 64: 93-106.

Shezi, S., Magwaza, L. S., Mashilo, J., Tesfay, S. Z. & Mditshwa, A. (2019). Photosynthetic efficiency and relationship to mesocarp dry matter content of ‘Carmen’ avocado (*Persea americana* Mill.) fruit in a cool subtropical climate. *Scientia Horticulturae* 253: 209-216.

Shezi, S., Magwaza, L. S., Mashilo, J., Tesfay, S. Z. & Mditshwa, A. (2020a). Photochemistry and photoprotection of ‘Gem’ avocado (*Persea americana* Mill.) leaves within and outside the canopy and the relationship with fruit maturity. *Journal of Plant Physiology* 246-247: 153130.

Shezi, S., Magwaza, L. S., Tesfay, S. Z. & Mditshwa, A. (2020b). Biochemical changes in response to canopy position of avocado fruit (cv. ‘Carmen’ and ‘Hass’) during growth and development and relationship with maturity. *Scientia Horticulturae* 265.

Silber, A., Israeli, Y., Levi, M., Keinan, A., Shapira, O., Chudi, G., Golan, A., Noy, M., Levkovitch, I. & Assouline, S. (2012). Response of ‘Hass’ avocado trees to irrigation management and root constraint. *Agricultural Water Management* 104(0): 95-103.

Snijder, B., Mathumbu, J. M. & Stassen, P. J. C. (2000). Pruning and managing existing avocado orchards. *South African Avocado Growers’ Association Yearbook* 23: 36-38.

Snijder, B. & Stassen, P. (1998). Manipulation of avocado trees to control tree size: A four year progress report. *South African Avocado Growers' Association Yearbook* 21: 58-62.

Snijder, B. & Stassen, P. J. C. (1995). Strategies for renewal of unproductive older avocado orchards with severe encroachment problems. *South African Avocado Growers' Association Yearbook* 18: 56-58.

Snijder, B. & Stassen, P. J. C. (1997). Can more intensive plantings of avocado orchards be maintained? *South African Avocado Growers' Association Yearbook* 20: 74-77.

Snijder, B. & Stassen, P. J. C. (1999a). Pruning mature and encroached avocado trees to restimulate and maintain production and fruit quality. *South African Avocado Growers’ Association Yearbook* 22: 51-54.

Snijder, B. & Stassen, P. J. C. (1999b). Training and manipulation of young avocado trees. *South African Avocado Growers’ Association Yearbook* 22: 62-68.

Stassen, P. J. C. (1999a).Planning and managing more intensive avocado orchards. In *Avocado Brainstorming*, 60-62 (Eds M. L. Arpaia and R. Hofshi). Riverside , California: Hofshi Foundation.

Stassen, P. J. C. (1999b).Revitalizing avocado jungles In *Proceedings of Avocado Brainstorming*, 63-65 (Ed M. L. A. a. R. Hofshi). Riverside, CA.

Stassen, P. J. C., Davie, S. J. & Snijder, B. (1995a). Principles involved in tree management of higher density avocado orchards. *South African Avocado Growers’ Association Yearbook* 18: 47-50.

Stassen, P. J. C., Davie, S. J. & Snijder, B. (1995b).Training young Hass avocado trees into a central leader for accommodation in higher density orchards. In *Proceedings of the III World Avocado Congress*, 251-254 Tel Aviv, Israel.

Stassen, P. J. C. & Snijder, B. (1996a). Manipulation of Hass avocado trees-pruning. *South African Avocado Growers' Association Yearbook (South Africa)*.

Stassen, P. J. C. & Snijder, B. (1996b). Manipulation of Hass avocado trees -- pruning. *South African Avocado Growers' Association Yearbook* 19: 73-76.

Stassen, P. J. C., Snijder, B. & Bard, Z. J. (1999a). Results obtained by pruning overcrowded avocado orchards. *Revista Chapingo Serie Horticultura* 5: 165-171.

Stassen, P. J. C., Snijder, B. & Donkin, D. J. (1999b). Results with spacing, tree training and orchard maintenance in young avocado orchards. *Revista Chapingo Serie Horticultura* 5: 159-164.

Symons, P. R. R. & Wolstenholme, B. N. (1990). Field trial using paclobutrazol foliar sprays on Hass avocado trees. *South African Avocado Growers’ Association Yearbook* 13: 35-36.

Thorp, T. G. (1992). A study of modular growth in avocado (*Persea americana* Mill.) In *Faculty of Agricultural and Natural Resource Sciences*, Vol. Doctor of PhilosophyAdelaide: The University of Adelaide

Thorp, T. G., Aspinall, D. & Sedgley, M. (1993). Influence of shoot age on floral development and early fruit set in avocado (*Persea americana* Mill.) cv. Hass. *Journal of Horticultural Science* 68(5): 645-651.

Thorp, T. G., Aspinall, D. & Sedgley, M. (1994). Preformation of node number in vegetative and reproductive proleptic shoot modules of *Persea* (Lauraceae) *Annals of Botany* 73(1): 13-22.

Thorp, T. G. & Sedgley, M. (1993a). Architectural analysis of tree form in a range of avocado cultivars. *Scientia Horticulturae* 53(1-2): 85-98.

Thorp, T. G. & Sedgley, M. (1993b). Manipulation of shoot growth patterns in relation to early fruit set in 'Hass' avocado (*Persea americana* Mill.). *Scientia Horticulturae* 56(2): 147-156.

Thorp, T. G. & Stowell, B. (2001). Pruning height and selective limb removal affect yield of large 'Hass' avocado trees. *HortScience* 36(4): 699-702.

Toerien, J. C. & Basson, A. M. (1979a). An investigation into thinning of an avocado orchard *South African Avocado Growers' Association Research Report* 3: 59-60

Toerien, J. C. & Basson, A. M. (1979b). An investigation into thinning of an avocado orchard. *Research Report, South African Avocado Growers' Association* 3: 59-60.

Westling, F., Underwood, J. & Bryson, M. (2021). A procedure for automated tree pruning suggestion using LiDAR scans of fruit trees. *Computers and Electronics in Agriculture* 187: 106274.

Whiley, A. W. & Anderson, G. (2002).Study tour of South Africa, New Zealand, the UK and the USA (also incorporating Chile)(report).

Whiley, A. W., Saranah, J. B., Wolstenholme, B. N. & Rasmussen, T. S. (1991). Use of paclobutrazol sprays at mid-anthesis for increasing fruit size and yield of avocado (*Persea americana* Mill. cv. Hass). *Journal of Horticultural Science* 66(5): 593-600.

Whiley, A. W., Schaffer, B. & Lara, S. P. (1992). Carbon-dioxide exchange of developing avocado (*Persea americana* Mill.) fruit. *Tree Physiology* 11(1): 85-94.

Whiley, A. W., Searle, C., Schaffer, B. & Wolstenholme, B. N. (1999). Cool orchard temperatures or growing trees in containers can inhibit leaf gas exchange of avocado and mango. *Journal of the American Society for Horticultural Science* 124(1): 46-51.

Whiley, A. W., Wolstenholme, B. N. & Faber, B. A. (2013).Crop management. In *The avocado: Botany, production and uses*, 342-379 (Eds B. Schaffer, B. N. Wolstenholme and A. W. Whiley). Wallingford, U.K.: CABI.

Wilkie, J. D., Conway, J., Griffin, J. & Toegel, H. (2019). Relationships between canopy size, light interception and productivity in conventional avocado planting systems. *The Journal of Horticultural Science and Biotechnology* 94(4): 481-487.

Winer, L. (2007).Effect of high density avocado orchard and root restriction on yield. In *VI World Avocado Conference*, 8pp Vina del Mar, Chile.

Witney, G. (May 2001). Canopy management as a strategy to increase returns. *Avo Research* 1(2): 1,6-7.

Wolstenholme, B. N. & Sheard, A. (2012). Avocado tree vigour and size dictate planting density: A South African perspective. *South African Avocado Growers' Association Avoinfo Newsletter* 185: 8-12.

Wolstenholme, B. N. & Whiley, A. W. (1995).Strategies for maximising avocado productivity: An overview. In *Proceedings of The World Avocado Congress III*, 61-70.

Wolstenholme, B. N. & Whiley, A. W. (1999). Ecophysiology of the avocado (*Persea americana* Mill.) tree as a basis for pre-harvest management. *Revista Chapingo Serie Horticultura* 5: 77-88.

Wolstenholme, B. N., Whiley, A. W. & Saranah, J. B. (1990). Manipulating vegetative: reproductive growth in avocado (*Persea americana* Mill.) with paclobutrazol foliar sprays. *Scientia Horticulturae* 41(4): 315-327.

Wolstenholme, B. N., Whiley, A. W., Saranah, J. B., Symons, P. R. R., Hofman, P. J. & Rostron, H. J. (1988). Paclobutrazol trials in avocado orchards: Initial results from Queensland and Natal. *South African Avocado Growers' Association Yearbook* 11: 57-59.

Woolf, A., Ferguson, I., Requejo-Tapia, L., Laing, W. & White, A. (1999). Impact of sun exposure on harvest quality of 'Hass' avocado fruit. *Revista Chapingo Serie Horticultura* 5: 353-358.

Wu, D., Phinn, S., Johansen, K., Robson, A., Muir, J. & Searle, C. (2018). Estimating changes in leaf area, leaf area density, and vertical leaf area profile for mango, avocado, and macadamia tree crowns using terrestrial laser scanning. *Remote Sensing* 10(11): 1750-1750.

Zilkah, S., Klein, I., Feigenbaum, S. & Weinbaum, S. A. (1987). Translocation of foliar-applied urea 15N to reproductive and vegetative sinks of avocado and its effect on initial fruit set. *Journal of the American Society for Horticultural Science* 112(6): 1061-1065.