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Review

Increasing the productivity of avocado orchards using high-density plantings: A review

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ABSTRACT

There is strong interest in the use of high-density plantings to increase the productivity of avocado (*Persea americana*) orchards. Close plantings have the potential for higher yields and returns than standard or traditional plantings, especially in the early years of production. The success of this technology is dependent on the use of methods to control shoot growth and maximise light interception as the trees begin to bear fruit. We reviewed the performance of high-density orchards in different environments, and the success of efforts to control the growth of the trees through the use of dwarfing material, canopy management and growth regulators. Close plantings generally produce higher yields in the first few years of bearing compared with the yields of standard plantings. However, in most growing areas, the trees in the close plantings soon begin to crowd each other and yields decline. This usually occurs despite efforts to control shoot growth by pruning the trees or by applying growth regulators. Efforts to breed dwarfing rootstocks that can control the growth of mature trees have been largely unsuccessful. In the absence of dwarfing material, effective canopy management appears to be the largest barrier to success of high-density orchards. Further research on the use of different pruning strategies and growth regulators to control the growth of the trees and maximise light interception is required. There are potential problems with some of the growth regulators persisting in the harvested fruit and soil under certain circumstances.

Contents

1. Introduction

Avocado (*Persea americana*) is a member of the family Lauraceae from central America, and has been cultivated for 4000–6500 years (Galindo-Tovar et al., 2008). It is one of the most important members of this family. Other popular large trees from the

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same family include cinnamon (*Cinnamomum camphora*), bay leaf (*Laurus nobilis*) and the camphor tree (*Cinnamomum zeylanicum*) (Schroeder, 1975). Total world production is more than 4.5 million tonnes, with about 25% of the crop traded around the globe (Bost et al., 2013). Nearly half of the international trade is from Mexico. During the past ten years, consumption of avocado has increased significantly throughout the developed and developing world. Mexico is the largest producer, with a total production of about 1.5 million tonnes (28% of world production). Other important producing countries are Chile (8%), Dominican Republic (7%), Indonesia (6%), Colombia (5%), Peru (5%), United States (5%), Brazil (4%), Kenya (4%) and Rwanda (3%). There is also strong interest in the crop in several other places, including Spain, Israel, South Africa and Australia. Mexico, Chile, Peru, Israel, Spain and South Africa are leading exporting countries (Chao and Paull, 2008).

Avocado is a subtropical to tropical tree, and can be grown successfully from the tropics to the subtropics at a latitude of 35°. There is a wide variation in the performances of the three races and various cultivars in different growing environments. Lines from the West Indian race (*P. americana* var. *americana*) are more suited to warmer conditions than lines from the Guatemalan (*P. americana* var. *guatemalensis*) or Mexican races (*P. americana* var. *drymifolia*) (Chao and Paull, 2008). Most cultivars are sensitive to water deficits, and to excess soil water caused by poor drainage. The trees are very susceptible to root rot caused by *Phytophthora cinnamomi* in areas with poor soils or high water tables.

Avocado trees are variable in shape, from tall upright specimens to widely spreading forms with multiple branches (Chanderbali et al., 2013). The trees can grow to heights of 15–18 m, with commercial orchards usually pruned to some degree. New growth occurs in flushes on terminal branches, with the trees usually producing one to three flushes each year, depending on the growing environment and agronomy (Rocha-Arroyo et al., 2011). Not all the branches on an individual tree may grow at the same rate or at the same time. The new leaves are relatively short-lived, and are often shed after about a year (Carr, 2013). Researchers in South Africa found that small avocado trees about 2.5–3.0 m high produced an average of 5.6 t per ha of leaf litter (dry weight) over two years (Murovhi et al., 2012). Most of the leaves fell in autumn in the first year, and in spring, summer and autumn in the second year. The inflorescences are borne on terminal and sub-terminal buds from shoots produced in spring and summer in the humid subtropics, and from these shoots and those produced in autumn in other growing areas. Only a small proportion of the flowers set fruit, and only a proportion of these fruitlets are carried to harvest. The period of fruit growth lasts six to fourteen months, depending on the cultivar and production environment. In some regions with cool climates, flowering may occur while the previous crop is still hanging on the trees.

Köhne (1989) studied the productivity of girdled branches and found that 'Fuerte' and 'Hass' required about five leaves (about 2900 cm^2) to produce an average fruit weighing about 290 g. Complete harvesting of all the fruit and leaves on a six-year-old 'Hass' tree indicated a yield of 52.8 kg and a total leaf area of 90.5 m^2, and a leaf to fruit ratio of 84. Similar data collected for a ten-year-old 'Fuerte' tree indicated a leaf to fruit ratio of 103. The number of leaves required to fill a fruit was much higher than that required to fill an apple fruit (15–20 leaves). Avocado requires more energy to grow a fruit than an apple because of the oil content of the fruit, and avocado leaves are larger (58 cm^2) than apple leaves (10–20 cm^2). Avocado trees also can photosynthesise all-year-round.

Avocado orchards are traditionally planted at wide spacings since the trees normally grow into large specimens. The trees are normally planted at 100–200 trees per ha (Köhne, 1988, 1993). Yield per unit growing area is low for the first few years after planting and then typically increases until the trees start to shade each other after about five to ten years and yields decline. Orchards are typically thinned once or twice over the next few years leaving 25–50 large trees per ha. In the humid tropics yields up to 28 t per ha have been recorded (Salazar-García et al., 2009), while in the dry subtropics, yields rarely exceed 12 t per ha (Wolstenholme and Whiley, 1995). Only a proportion of the available area is usually planted to allow access for spraying and harvesting. Harvesting fruit from large trees is very expensive. There has been strong interest in the use of high-density plantings to increase productivity and returns, especially in the early life of orchards. This approach has been successful in some temperate fruit crops such as apple, pear, plum and olive (Jackson, 1989; Wertheim et al., 2001; Milosevic et al., 2008; Freixa et al., 2011; Rallo et al., 2013; Connor et al., 2014).

Traditional apple orchards based on wide plantings yielded 5 t per ha, whereas modern orchards based on close plantings, dwarfing rootstocks and effective canopy management yield up to 100 t per ha (Jackson, 1989). The canopies of most orchard crops, including those from temperate and tropical areas capture less than 70% of radiated light and intensive canopy management is required to maximise light interception and productivity (Whiley et al., 2013). The development of high-density orchards in avocado is dependent on the development of small trees than can be pruned to maximise light interception and still remain productive.

This paper reviews research undertaken to increase the productivity of avocado through the use of high-density plantings. Information is presented showing the relative productivity of traditional and high-density orchards in different growing areas. Strategies used to control the growth of the trees are explored. These include the use of dwarfing rootstocks, canopy management and the applications of growth regulators. Suggestions are provided on future research which may lead to better control of tree growth and better light interception in new plantings.

2. Productivity and light interception in avocado, and high-density orchards in other crops

The bulk of the energy from the solar radiation falling on the Earth's surface contributes to evaporation of water and the heating of plants and soil, with only 1–2% used by plants in photosynthesis (Turner, 1994). The amount of carbon fixed by plants depends on environmental conditions and the physiology of the leaves. The distribution of light and leaf nitrogen with a tree is usually a reliable indication of potential photosynthesis by the canopy. There are conflicting reports about the effects of light on carbon assimilation in the leaves and canopies of avocado, and little information about the effect of light on tree growth and production, or the optimum canopy layout for capturing light.

A light response curve quantifies the relationship between net CO_2 assimilation and photosynthetic photon flux (PPF), also referred to as photosynthetically active radiation (PAR). This refers to the number of photons in the spectral wavelength from 400 to 700 nm. Net CO_2 assimilation for individual leaves of avocado trees grown in pots was saturated at a relatively low value of PPF of about 500 μmol per m^2 per s (Scholefield et al., 1980). The equivalent value for whole canopies of trees grown in pots was slightly higher at 660 μmol per m^2 per s (Bower et al., 1978). This is equivalent to about a third to a quarter of full sun. The higher value of saturation for a canopy compared with the value for an individual leaf is due to a portion of the canopy being shaded in mature trees. The values of PPF saturating net CO_2 assimilation are normally higher for trees growing in the field than for trees growing in containers (Whiley et al., 1999). These authors found that net CO_2 assimilation in individual leaves in trees growing in the field was saturated at a PPF of about 1100 μmol per m^2 per s, or about half full sun.

Research conducted in California showed that leaves of avocado maintain high rates of photosynthesis for only short periods of their lives (Liu et al., 2002). Net CO_2 assimilation in leaves emerging in spring reached a maximum about 50 days after they emerged and then declined. Leaves of the flush produced in autumn had high rates of net CO_2 assimilation (maximum values of about 20 μmol CO_2 per m^2 per s) when measured in spring, which increased with increasing light levels up to about 1500 μmol per m^2 per s. In contrast, when these leaves were measured in summer, net CO_2 assimilation was much lower (maximum values of about 4 μmol CO_2 per m^2 per s) and relatively unresponsive to light levels.

Medina-Torres et al. (2011) collected similar information to the study in California for several cultivars growing in Mexico. They sampled mature leaves at different times of tree growth, presumably from different flushes (winter, spring and summer). They found that net CO_2 assimilation reached a maximum from late November to late February during fruit growth (about 30 μmol CO_2 per m^2 per s) with lower values at other times (about 18 μmol CO_2 per m^2 per s). It can be concluded that leaves emerging at different times have different maximum rates of photosynthesis. There are also differences in the efficiency of individual leaves at different stages of tree phenology.

There has been limited research on the effect of light on the growth and productivity of avocado. Chirachint and Turner (1988) grew young 'Fuerte' plants in containers under shade (PPF of about 735 μmol per m^2 per s) or full sun (PPF of about 1350 μmol per m^2 per s) for six weeks in southern Western Australia. They found that shading had no effect on the growth of the leaves, stems or roots. This was possibly because photosynthesis was saturated in the shaded plants or because the plants used reserves accumulated in the different tissues before the experiment started. There have been no studies exploring the effect of light on leaf area expansion, flowering, fruit set and yield.

Total dry matter production and yield in tree crops is a function of the amount of light intercepted by the canopy. Studies in apple have shown that the distribution of light within the tree influences the proportion of the canopy which has sufficient light to produce fruit (Jackson, 1980). If the canopy is evenly distributed over the orchard surface through the use of even-spaced dwarfed trees or horizontal or angled trellises, the canopy can be relatively shallow (low leaf area indices) for optimum distribution of light through the canopy (Jackson, 1989). In contrast, much denser canopies (higher leaf area indices) are required to intercept light in widely spaced orchards. The application of these studies in apple to high-density avocado orchards is unknown. Avocado trees set most of their crop on the terminal branches that are typically in the full sun. It is not known if shading in the lower sections of the canopy reduces the productivity of the whole canopy.

Researchers in South Africa have explored different canopy management options in avocado (Stassen et al., 1995). These workers concluded that the optimum tree shape was conical or pyramidal. Hedgerows were also recommended, with at least 1.8 m between adjacent rows. They also recommended that the height of the trees must not be more than 80% of the distance between the rows. None of these recommendations were based on an analysis of the effect of tree shape and height on the interception of light by different parts of the canopy. Whiley et al. (2013) noted that fruit production is often compromised by the intensive pruning regime required to control the growth and shape of the trees. Thorp and Sedgley (1993a) investigated the architecture of several avocado cultivars in Australia. They found that there were consistent differences in tree shape, tree height, crown diameter and number of major limbs amongst the cultivars four years after grafting. For instance, 'Reed' was very upright with 2.8 major limbs, while 'Sharwil' was spreading with 4.2 major limbs. 'Hass' was intermediate in height and had 3.7 major limbs. The cultivars also had different numbers of branches, which are potential fruiting sites. It was suggested that pruning could be used to increase the productivity of cultivars that have few branches.

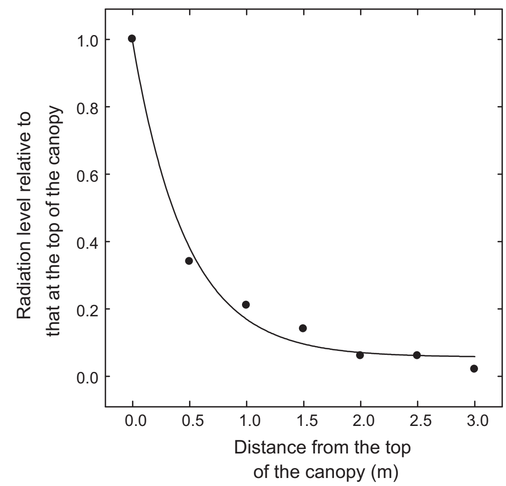

Fig. 1. Extinction of light through the canopy of 'Hass' avocado hedgerows in Israel in June. The exponential decay function shows that relative light levels decreased as the distance from the top of the canopy increased.

Adapted from Hadari (2004).

Research conducted in Australia and Spain on light interception, canopy development and productivity in olive has some relevance to high-density avocado orchards. The olive trees were grown in hedgerows with different heights and widths. There were strong correlations between fruit size and the percentage of oil in the fruit in different parts of the canopy, and incident radiation (Connor et al., 2013). Daily shortwave solar radiation declined exponentially from about 9 MJ (mega joule) per m^2 per day at the top of the canopy to about 2 MJ per m^2 per day at the bottom of the canopy. Other work revealed that maximum yields were achieved when the depth of the canopy was the same as the width of the interrows (Connor and Gómez-del-Campo, 2013). Sloping canopies (10°) were found to be more productive than straight-sided canopies (0°). These ideas have been only superficially explored in avocado.

The relationship between productivity and light interception is not well understood in avocado. Hadari (2004) collected data on the extinction of sunlight in the canopy of trees growing in Israel over a single season. The measurements were taken on a hedgerow planting of 'Hass' trees that were about 3 m high in June. The results of the experiment showed that light levels decreased quickly through the tree's canopy, and was only about 20% of ambient levels 1 m into the canopy (Fig. 1). This level of light was considered satisfactory for the photosynthesis required to support the developing crop. Hadari also simulated the interception of light in different planting systems. Individual closely planted trees were found to be potential more productive than hedgerows, in terms of capturing the amount of light required to support a heavy crop. High light levels were mainly found in the top of the hedges, whereas light was more uniformly distributed in individual trees. When comparing different hedgerows, dwarf trees were better than tall trees, close plantings were better than wide plantings, and trees with the sides pruned to sharp angles were better than trees pruned to wide angles. It was suggested that fruit should be located in parts of the canopy receiving at least 20% of full sun. Hadari collected information on the number of fruit at different positions in the canopies of the trees, but the data were too variable to relate these to light levels.

Table 1
Effect of pruning on the interception of sunlight in the lower canopy of 16-year-old 'Hass' trees in South Africa. Light levels were measured 1.5 m above the ground and 1.0 m from the edge of the canopy, and are expressed as a percentage of ambient conditions. The trees needed to be pruned in winter and summer to have high light levels in the lower canopy in summer.

Treatment/time of measurement	Light levels (% of ambient)	
	1995	1996
Control	7	7
In July after pruning	58	38
In summer, after pruning in July	11	9
In summer, after pruning in July and summer	40	32

Adapted from Stassen and Snijder (1996).

Research conducted in South Africa showed that the benefits of pruning on improving light levels in the lower sections of the canopy can be short-lived unless the initial intervention is followed up by additional pruning (Stassen and Snijder, 1996). The trees needed to be pruned in winter and summer to have high light levels in the lower canopy in summer (Table 1). This was because pruning in July encouraged strong vegetative growth in spring and summer.

Corelli-Grappadelli and Marini (2008) reviewed planting systems in peach, and discussed production in relation to planting density and tree form. They reported on several experiments where either tree density or tree form was varied, and others where both parameters were varied. In the first part of the research where tree density was varied, most authors found that yield per hectare increased less proportionally to tree density. For instance, Bargioni et al. (1985) working with densities of 1250, 1665 or 2500 trees per ha, concluded that the medium density provided the highest profits. The trees planted at the highest density had slightly higher yields than the trees planted at the medium density, but the additional costs of planting were not justified. Corelli-Grappadelli and Marini (2008) concluded that the yield of trees planted at high densities is eventually limited by the amount of light than can be intercepted by the orchard. Training system generally only affected productivity in the early life of plantings.

Robinson (2003) analysed the effect of planting density on the yields and economic returns of apple orchards in different growing areas. Data from several studies showed that yields on a hectare basis were related to planting density in the early years of the orchard. The most closely planted orchards produced the highest cumulative yields. The relationship between cumulative yield and tree density was linear in the first two to three years after planting. However, by year six, the relationship was curvilinear. Robinson presented data from a study conducted in New York in the United States over eleven years. At the lower planting densities (1000–2000 trees per ha), there was an additional yield of 150 kg per ha for each additional tree per ha. This would be about eight times the costs of the additional tree. At very high densities 3000–4000 trees per ha), the gains in yields were equivalent to 1–3.5 times the costs of the additional tree.

Palmer et al. (1989) and Balkhoven-Baart et al. (2000) reported similar responses in other growing areas, including the Netherlands. In most apple-producing areas, the optimum tree density in terms of economic returns is between 1000 and 3000 trees per ha. The super-high-density plantings have greater risks than the moderately high-density plantings due to the high investment costs and the difficulty of managing the balance between vegetative and reproductive growth.

It is apparent that moderately dense plantings are more economical than less dense plantings in many temperate crops such as apple, peach and olive. The development of these plantings has been dependent on an understanding of the relationship between productivity, fruit quality and the interception and distribution of light through the canopy. In the temperate tree crops, dwarfing rootstocks and intensive canopy management have been essential features of the new plantings. We have a poor understanding of the relationship between productivity and light in avocado orchards. Optimum tree shapes, sizes and leaf areas have not been described even for the two main commercial cultivars.

3. Productivity of avocado orchards

There is little information on the long-term productivity of avocado orchards. Most authors report on the yields of trees in research experiments for only a few years. Trees can also be susceptible to alternate (biennial) bearing which affects the calculation of average productivity. Examples of seasonal yields for 'Fuerte' and 'Ettiinger' in Cyprus (Gregoriou, 1992), and for 'Hass' in Australia (Thomas, 1997) and California (Mickelbart et al., 2012a) are shown in Fig. 2. For the 'Fuerte' trees growing in Cyprus, there was general trend for yields to increase over time, with a very poor crop at the end of the experiment. The yields for 'Ettinger' were much more variable, reflecting a possible alternate bearing pattern.

Yields for 'Hass' in California showed a strong alternate bearing pattern, with no evidence of productivity increasing over time (Mickelbart et al., 2012a). Low yields in individual year were related to later and shorter periods of flowering and fewer and larger fruit. In the study by Mickelbart et al. (2012b), there was no direct relationship between alternate bearing, and shoot and root growth. However, Lovatt (2010) indicated that the "on" crop inhibits the number of new vegetative shoots produced over summer. Data from Australia show the productivity of low- and high-yielding trees in a single orchard growing in a cool climate in southern Queensland (Fig. 2). The performance of the better trees was relatively stable, apart from higher yields in year eight. In contrast, the yields of the poorer trees showed an on/off pattern. These results indicate that alternate bearing can make it difficult to assess the effect of planting systems and tree agronomy on the performance of avocado orchards in long-term experiments. Mickelbart et al. (2007) overcame some of these issues by averaging yields over consecutive two-year periods (years 5/6 versus years 7/8, etc.).

4. High-density orchards

There has been much discussion about the potential of high-density plantings in avocado, but few studies demonstrating the long-term economic benefits (Hofshi, 1998). In most of the experiments conducted so far, the high-density orchards were initially very productive, but yields soon decreased as the tress began to crowd each other. Inappropriate or the lack of canopy management often reduced the productivity of potentially high-yielding trees. Most of the researchers abandoned their experiments. Several studies have been conducted in South Africa and a few studies conducted in Israel, California and Chile. None of the experiments ran for more than ten years.

Köhne and Kremer-Köhne (1991) compared the productivity of standard and close plantings (400 or 800 trees per ha) of 'Hass' trees on 'Duke 7' rootstock in South Africa. The trees were planted in 1986, with the first crop harvested in 1988, and the last crop harvested in 1990. The trees grown in the close plantings were injected or drenched with the growth regulator paclobutrazol, whereas the trees grown in the standard plantings were not. None of the trees were pruned. Cumulative yields per tree were similar in the two treatments, whereas cumulative yields per hectare were 95% higher in the close planting (Table 2). The higher cumulative productivity per hectare in the close planting just reflected the greater planting density. Although establishment costs were about 15% higher for the close planting, the return on investment occurred earlier for

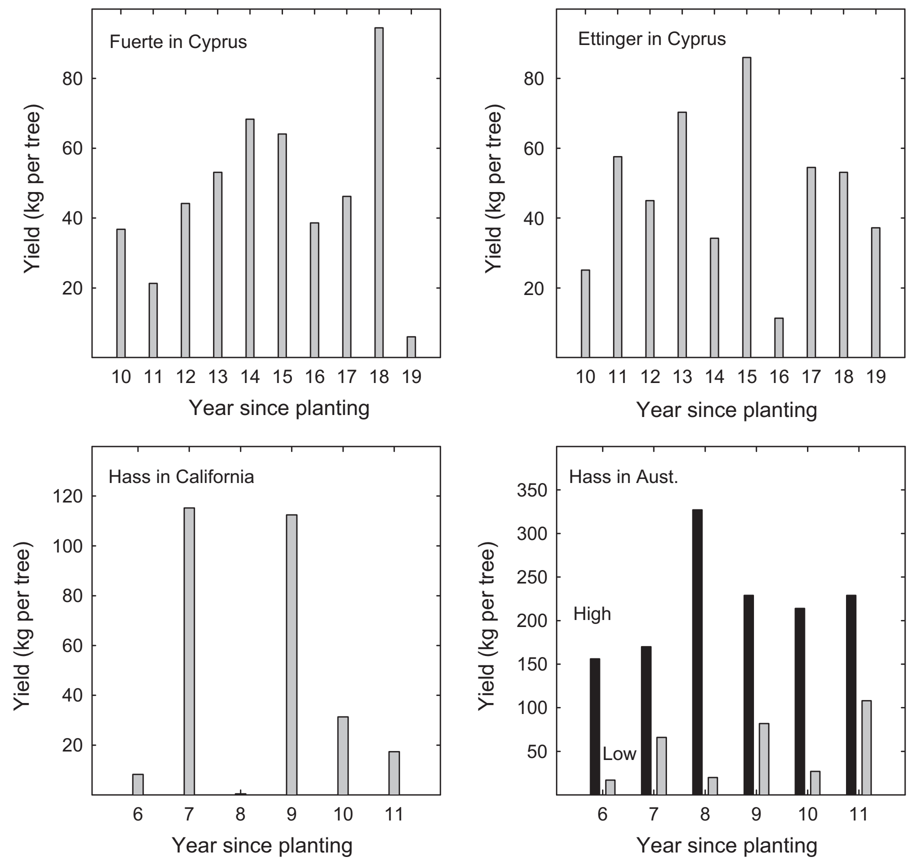

Fig. 2. Yields of avocado trees in Cyprus (adapted from Gregoriou, 1992), Australia (adapted from Thomas, 1997) and California (adapted from Mickelbart et al., 2012a). The data for 'Hass' in Australia show the productivity of low- and high-yielding trees in a single orchard. In Cyprus and California, there was some evidence of alternate bearing in 'Ettinger' and 'Hass', but none in 'Fuerte'. In Australia, the yields of the heavy-bearing trees were relatively stable (no alternate bearing), whereas the yields of the low-bearing trees were highly variable (alternate bearing).

Table 2
Effect of planting density and paclobutrazol on the yield of 'Hass' avocado trees in South Africa. The trees grown at high density (800 trees per ha) were drenched or injected with paclobutrazol, whereas the trees grown at low density (400 trees per ha) were not treated with paclobutrazol. None of the trees were pruned. The trees were planted in 1986. The experiment was eventually abandoned because the researchers were unable to control the growth of the trees.

Treatment	Yield (kg per tree)			Cumulative yield (1988–1990)	
	1988	1989	1990	Yield (kg per tree)	Yield (t per ha)
Low density	0.2	26.8	17.0	44.0	17.6
High density	1.9	21.3	19.8	43.0	34.4

Adapted from Köhne and Kremer-Köhne (1991).

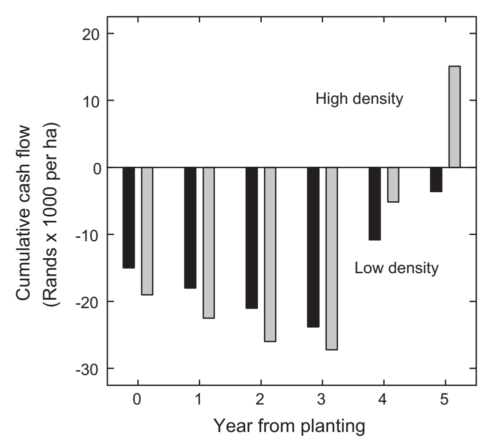

Fig. 3. Cumulative cash flow in 'Hass' avocado trees planted at low or at high densities in South Africa. The trees grown at high density (800 trees per ha) were drenched or injected with paclobutrazol, whereas the trees grown at low or standard density (400 trees per ha) were not treated with paclobutrazol. The trees were planted in 1986. The results show that the trees grown at low density had not achieved a positive cash flow after five years, whereas the trees grown at high density had. Adapted from Köhne and Kremer-Köhne (1991).

the trees planted closely together. After five years, the close planting had a profit of R15,000 per ha, whereas the standard planting had not yet covered the costs of establishing the orchard (Fig. 3). The experiment was eventually abandoned because the researchers were unable to control the growth of the trees. This experiment may have continued for longer if the trees had been pruned regularly.

Stassen et al. (1999a) conducted similar work a few years later, once again in South Africa. They compared the productivity of medium and close plantings (667 or 1666 trees per ha), using 'Hass', 'Fuerte', 'Pinkerton', 'Edranol' and 'Ryan' grafted onto 'Duke 7' rootstocks. The trees were planted in 1995, with yields collected from 1997 to 1999. Cumulative yields per tree in the close plantings were 20–40% of those of the medium plantings (Table 3). Cumulative yields per hectare were similar between the two plantings for 'Fuerte', and 16–60% higher for the close plantings compared with the yields of the medium planting for the other cultivars. However, the high productivity of the close plantings could only be maintained with severe pruning. An earlier report by these authors showed that tree growth up to 1998 was similar in the two planting systems (Snijder and Stassen, 1999) suggesting potential over-crowding in the close planting.

Table 3
Effect of planting density on the yield of five avocado cultivars in South Africa. The trees were grown at medium (606 trees per ha) or high density (1667 trees per ha). The trees were planted in 1995, with yields collected from 1997 to 1999. All the trees were shaped as central leaders in the nursery and selectively hand pruned. The 'Fuerte' trees were drenched with paclobutrazol. The high productivity of the close plantings could only be maintained with severe pruning.

Cultivar	Cumulated yield (kg per tree)		Cumulative yield (t per ha)	
	Low density	High density	Low density	High density
Fuerte	23.4	5.2	9.4	8.7
Hass	36.8	14.1	14.7	23.6
Pinkerton	39.4	13.8	15.8	23.0
Edranol	58.2	18.0	23.3	29.9
Ryan	42.2	11.8	16.9	19.6

Adapted from Stassen et al. (1999a).

Over the same period, Stassen et al. (1999b) compared the yields of 'Hass' trees planted at standard (400 trees per ha) or high density (800 trees per ha). The trees were planted in 1994, with yield data collected from 1997 to 1999. The trees in the close planting were pruned to a central leader and selectively pruned at other times, while the trees in the standard planting were left unpruned. There was no difference in the productivity of the two plantings on a hectare basis possibly because pruning reduced the yield of the trees in the close planting. Cumulative yields were 19.8 t per ha in the medium planting and 18.5 t per ha in the close planting. Regular light pruning is probably more effective for maintaining productivity than irregular heavy pruning.

Snijder and Stassen (1999) reported on other small experiments, where they examined the effect of planting density on the performance of 'Hass' trees growing in South Africa. In the first investigation, they compared the yields of trees grown at medium (400 trees per ha) or high density (800 trees per ha). The trees grown at the wider spacings were left unpruned, while the trees grown at the close spacings were pruned. The trees were planted in 1994, with fruit yields collected in 1997 and 1998. Cumulative yields over this period were slightly higher in the trees from the wider spacings (10.8 t per ha) than those from the trees in the close spacings (8.1 t per ha). In the second investigation, the authors compared the productivity of trees grown at medium (606 trees per ha) or close spacings (1667 trees per ha). The trees were planted in 1995, left unpruned, with yields collected in 1997 and 1998. Cumulative yields were about 50% higher in the close planting (7.7 t per ha) than in the medium planting (4.9 t per ha). The results of experiments conducted in South Africa suggest that trees planted at high density were initially productive. However, the lack of an appropriate method of managing the size of the canopy led to the trees crowding out each other and becoming unproductive. In other instances, excessive pruning reduced the productivity of the trees planted closely together.

Razeto et al. (1995) investigated the effect of planting density on the productivity of 'Bacon' trees growing on 'Mexicola' rootstocks in Chile. The trees were grown at low (277 trees per ha), medium (600 trees per ha), or high densities (1250 trees per ha). The trees were planted in 1984 (year 0) and cropped from 1987 to 1992 over eight years. The trees were not pruned, thinned, or sprayed with growth regulators during the study.

Yield per tree in the low density plots increased up to year 7 and then decreased slightly (Fig. 4). Yield per tree in the medium density plots increased up to year 6 and then stabilised, while yield per tree in the high density plots increased up to year 7 and then decreased. There were different patterns of production over time when productivity was expressed on a unit area basis. Yield per hectare in the low and medium density plots increased up to year 6 and then stabilised, while yield per hectare in the high density plots increased up to year 7 and then decreased (same pattern as yield per tree for this treatment). Cumulative yield per tree decreased as planting density increased, whereas cumulative yield per hectare increased (Table 4). These results indicate that cumulative productivity per unit area was higher with high densities than with low densities, but yields in the close plantings eventually started to decline. These results also highlight the need for effective canopy management in dense orchards in the absence of dwarfing rootstocks and naturally small trees. The canopies of the trees planted at the medium and high densities began to grow into each other by year four or five, in the absence of any pruning.

Winer (2007) reported on the effect of planting density and root restriction on the performance of 'Hass' and 'Ettinger' trees growing in Israel. The trees were grown at densities of 1250 or 1670 trees per ha. The roots of the trees in both treatments were restricted by placing a plastic sheet perpendicular to the ground 0.5 deep on both sides of the trees along the rows. The trees were planted in July 2003, with data on yield shown for the crop harvest

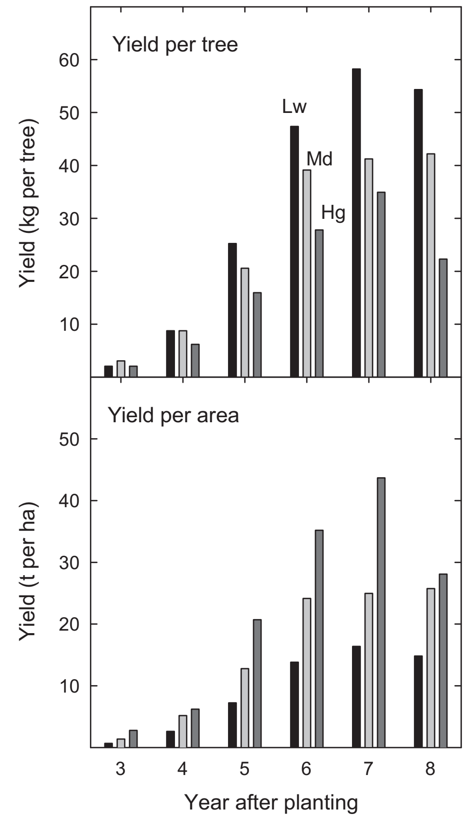

Fig. 4. Effect of planting density on the yield of 'Bacon' avocado trees in Chile. The trees were grown at low (Lw, 277 trees per ha), medium (Md, 600 trees per ha) or high densities (Hg, 1250 trees per ha). The trees were planted in 1984, with yields collected from 1987 to 1990. The trees were not pruned or treated with growth regulators. The canopies of the trees grown at medium or high densities started to grow into each other by years 4 or 5, and yields either stabilised or decreased.
Adapted from Razeto et al. (1995).

Table 4
Effect of planting density on the cumulative yield of 'Bacon' avocado trees in Chile. The trees were grown at low (277 trees per ha), medium (600 trees per ha), or high densities (1250 trees per ha). The trees were planted in 1984, with yields collected from 1987 to 1990. The trees were not pruned or treated with growth regulators. Cumulative productivity per unit area was higher with high densities than with low densities, but yields in the close plantings eventually started to decline.

Cumulative yield	Low density	Medium density	High density
Yield (kg per tree)	83.4	71.6	52.0
Yield (t per ha)	24.4	43.5	64.9

Adapted from Razeto et al. (1995).

30 months later in 2005/2006. At this time, there were no differences in the productivity of the two plantings in either cultivar. No more reports on this study have been published.

Snaddon and Reay (1995) analysed the profitability of standard and close plantings of 'Hass' avocado trees in South Africa. They compared the costs and returns of orchards planted out at 400 or 800 trees per ha, and used the internal rate of return (IRR) as an indication of the overall rate of return produced by the cash flow over the investment period. They found that there was little difference in the IRR for the two planting systems. The payback period was no shorter for the close planting than for the open planting, and the maximum negative exposure in the second year was about 22% (R8000 per ha) greater for the close planting. Snaddon and Reay based their analysis on the yields of trees grown at a density of 200 trees per ha from an earlier study by Wolstenholme and Kaiser (1991). No data were presented for trees grown at higher densities. Trees growing at 400 or 800 trees per ha would have lower yields on a per tree basis than trees growing at 200 trees per ha. The estimated productivity of the trees grown at high density calculated by Snaddon and Reay is probably too high.

It can be concluded that high-density plantings have not been successful in most avocado-growing areas. Initial results in countries such as South Africa were encouraging with greater production on an area basis in the dense plantings than in the traditional plantings. However, eventually the trees started to crowd each other and production declined. Efforts to control shoot growth and maintain the trees at a manageable size have been generally unrewarding. Pruning often reduced productivity, at least for a few seasons. In the absence of any canopy management, large sections of the trees typically became shaded and unproductive. Large trees are also difficult to spray and harvest. There have been some successes with dense plantings in a few places such as California and Chile (see later). However, the success of these orchards is usually dependent on particular cultivars (upright) or growing conditions (poor soils and dry, cool climates) that are not applicable to most commercial situations.

5. Use of pruning to control tree growth

Overcrowding poses a serious problem for orchard access and, more importantly, for adequate light interception needed for successful photosynthesis, flowering and fruit set. Much research has been undertaken on the use of pruning (canopy management) to rejuvenate old, overcrowded orchards. In these orchards, pruning can be used to increase the distribution of light through the canopy, although productivity is not always restored in the same season (Crane et al., 1992; Ernst and Ernst, 2011; Stassen et al., 1999a; Whiley et al., 2013). For instance, heavy pruning of 34-year-old trees of 'Lula' and 'Booth 8' in Florida inhibited production for the following two to three years (Crane et al., 1992). Extensive studies have been conducted in Australia to examine the effect of canopy management strategies on the productivity of mature orchards (Leonardi, 2008). It was concluded that in warm subtropical coastal areas, hedging was best for controlling tree growth and maintaining productivity, while in cool temperate areas where successive crops often overlap, selective limb removal was more effective.

Thorp and Stowell (2001) reported on the effect of pruning on the productivity of 'Hass' trees growing in New Zealand. The trees were planted in 1986, with the trees pruned 4 or 6 m above the ground in 1994. A set of unpruned trees was used as controls. Cumulated yield from 1994 to 1996 was similar in the controls (573 kg per tree) and the trees pruned 6 m above the ground (524 kg per tree), and lower in the trees pruned 4 m above the ground (426 kg per tree). Even though the more severe pruning reduced productivity compared with that achieved in the unpruned trees, picking costs were reduced because the treatment increased the number of fruit that were harvested 2–4 m above the ground. It was suggested that pruning earlier in the life of the orchard was less likely to reduce production than pruning once the canopy was well established.

Several authors have suggested that the new trees should be pruned to particular shapes for optimum productivity or that individual trees should be removed after five years in crowded orchards (Snijder and Stassen, 1997; Stassen et al., 1995, 1999a,b). Various recommendations have been suggested, including pruning the trees to a pyramidal central leader or to a height of no more than 80% of the width of the row to improve the interception and distribution of light through the canopy. Some authors have recommended that non-spreading upright cultivars such as 'Hass' and others be used for high-density orchards (Razeto et al., 1995; Stassen et al., 1999b).

There have been few data sets collected indicating the benefits of early pruning, pruning trees to particularly shapes or heights, or the advantages of particular cultivars for high-density plantings. The results of some of these investigations are reported here. Snijder et al. (2000) examined the effect of different pruning strategies on the performance of mature 'Hass' trees growing in South Africa. In the first experiment, 12-year-old trees were monitored for two years, pruned at different rates and yield recorded the following year. The trees were beginning to crowd each other at the start of the experiment, with yields of the control trees in 1998 and 1999 only about half of those recorded in 1997 (Table 5). Their work showed that drastic pruning of the whole tree reduced production, whereas less drastic pruning of the whole tree or pruning only part of the tree maintained production.

In the second experiment, Snijder et al. (2000) evaluated two different pruning strategies on the performance of 'Hass' and 'Fuerte' trees growing in a hot, dry climate where excessive tree growth was less of an issue. The trees were 12- to 16-years old at the start of the experiment. In the first treatment, the whole of individual trees was pruned to a pyramid shape. In the second treatment, different sides of the trees were pruned in alternate years. Yields were collected before and after the trees were pruned. The response to pruning varied with the cultivar (Table 6). Pruning had no effect in 'Fuerte', with similar yields before and after pruning. In contrast, in 'Hass' yields were about 60% higher after pruning, with no difference between the two different strategies. These results showed that pruning can maintain production or even increase it when trees are growing in an environment that restricts vegetative growth. This response was different to that recorded in the first experiment where the more favourable environment promoted growth.

Stassen et al. (1999a) reported on the recovery of mature orchards in South Africa following pruning to improve light interception and distribution through the canopy. The four main experiments involved 'Hass' and 'Fuerte' trees planted at 204–278 trees per ha. The trees were 7-, 8- or 12-years old when they were first pruned, and were monitored for up to four years before and after the initial pruning. In the first two experiments, average yields before and after pruning were similar at about 10 t per ha (Fig. 5). There was a different response in the other two experiments, with average yields before pruning of about 2.5 t per ha compared with 12.0 t per ha after pruning. Yields varied over the seasons in the different production periods probably reflecting different growing conditions. The higher average yields in the trees that were pruned in the last two experiments probably reflects the greater overcrowding and neglect in those orchards. Productivity in these two orchards decreased again two years after pruning, suggesting that the trees started to crowd each other again.

Roe and Köhne (1996) reported on the productivity of 'Hass' trees grown as hedgerows in South Africa. The orchards were

Table 5
Effect of pruning on the yield of 'Hass' avocado trees in South Africa. Control trees were left unpruned, while the other trees were pruned to remove selected branches along the sides, or hedged. The trees were 12-years old at the start of the experiment and were grown at a density of 204 trees per ha. The trees were pruned after harvest in 1998 and before harvest in 1999. Drastic pruning of the whole tree reduced yield, whereas less drastic pruning of the whole tree or pruning only part of the tree maintained production.

Treatment	Yield (t per ha)		
	1997	1998	1999
Control	23.7	14.9	11.5
Light selective pruning of whole tree			19.9
Heavy selective pruning of whole tree			25.4
Light pruning of one side of the tree in year 1 and then on the other side in year 2			20.2
Heavy pruning on both sides of the tree			10.7

Adapted from Snijder et al. (2000).

Table 6
Effect of pruning on the yield of 'Fuerte' and 'Hass' avocado trees in South Africa. The trees were 12- to 16-years old at the start of the experiments and were grown at a density of 204 trees per ha, and were just starting to crowd out each other. The trees were pruned after harvest in 1998. Pruning maintained production or even increased it when trees were grown in an environment that restricted vegetative growth.

Treatment	Fuerte		Hass	
	Yield before pruning (t per ha)	Yield after pruning (t per ha)	Yield before pruning (t per ha)	Yield after pruning (t per ha)
Pruning of one side of the tree	18.2	15.4	14.5	24.1
Pruning of the whole tree	16.8	18.4	14.1	23.4

Adapted from Snijder et al. (2000).

set up with 200 trees per ha in a hot, dry site (Moketsi), or with 400 trees per ha in a warm, moist site (Evenrond). They concluded that excess shoot growth made it difficult to recommend hedgerows at the warm, moist site, with yields more stable at the hot, dry site.

There have been many experiments to examine the effect of canopy management on the performance of avocado trees growing in Australia (Leonardi, 2005). Trees were pruned at various times, from after harvest to before flowering. The fruit were harvested in August. Pruning generally reduced yields in the first year when up

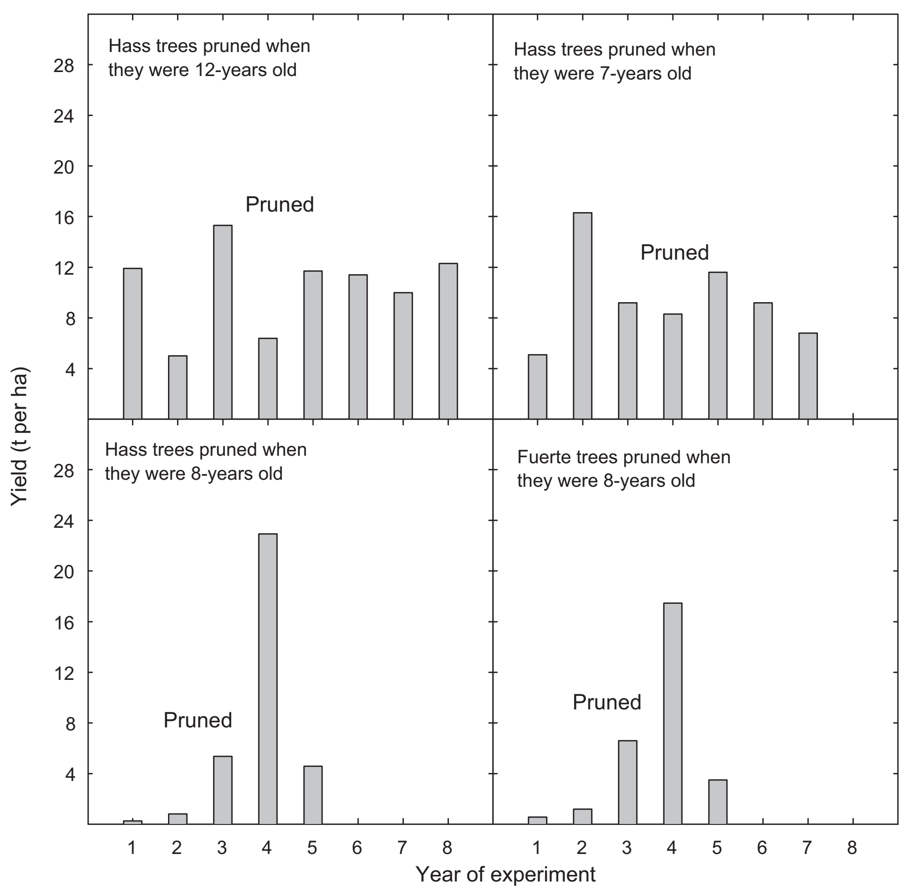

Fig. 5. Effect of pruning on the yield of 'Hass' and 'Fuerte' trees in South Africa. Pruning had a variable effect on the productivity of the trees. In two cases, yields were relatively similar before and after pruning (top). In the other two cases, yields increased initially after pruning, and then decreased (bottom).
Adapted from Stassen et al. (1999a).

Table 7
Effect of pruning on the yields of six-year-old 'Hass' avocado trees in subtropical Australia. The trees were grown at 333 trees per ha. About 2.0–2.5 m was removed from the canopy in the first year, and about 1.0 m in the second year. In the second year, the trees pruned after harvest had similar yields as the controls, with lower yields in the other treatments. Pruning tended to reduce fruit quality compared with that observed in the controls.

Treatment	Yield (t per ha) in 2001	Yield (t per ha) in 2002
Control	23.4	14.9
Pruned after harvest in September	10.2	14.9
Pruned after harvest and in December	10.4	10.5
Pruned after harvest and in January	16.0	10.1
Pruned after harvest and in February	11.7	7.4

Adapted from Leonardi (2005).

to 2.5 m was removed from the canopy. There were mixed effects of the time of pruning on the yields of the trees in the subsequent year when about 1.0 m was removed from the canopy (Table 7). Trees pruned immediately after harvest had similar yields as the controls, whereas the trees pruned at this time and later had lower yields. Pruning tended to increase the incidence of fruit rots compared with the incidence in the control trees. This was possibly associated with the strong vegetative growth in the trees pruned. This work showed that pruning can influence both productivity and fruit quality in subtropical Queensland.

Numerous researchers have investigated the effect of canopy management on the performance of avocado orchards. Experiments have been conducted in several growing areas, including Australia, South Africa, Florida and Israel. The studies have been fairly broad, and have included the responses of newly planted trees, mature orchards and even neglected crowded orchards where much of the canopy had become non-productive. There has been some effort to determine the optimum time and type of pruning to maintain productivity and fruit quality. Most of these studies have been conducted independently of a good understanding of the effect of light on the productivity of different sections of the canopy. Further studies are required to determine the optimum time of pruning during the growth cycle in different growing areas.

It is generally considered that canopy management should start early in the life of the orchard. Overall, regular light pruning is more effective than heavy pruning on a less regular basis. Heavy pruning, or even light pruning at the wrong time can reduce productivity. There are several cases where heavy pruning has reduced bearing for several seasons. There is some information that different strategies are required for different growing areas, with growers producing fruit in warmer areas having more options than growers producing fruit in cooler areas where successive crops overlap on the trees.

6. Use of growth regulators to control tree growth

Pruning often leads to strong regrowth of the shoots in avocado (Arpaia et al., 2007; Stassen et al., 1999a). Plant growth regulators such as paclobutrazol, uniconazole and prohexadione-calcium have been evaluated to determine whether they can control this excessive shoot extension.

Köhne and Kremer-Köhne (1989) were some of the earlier researchers who investigated the effect of chemicals on the growth of avocado, using young 'Edranol' seedlings grown in a glasshouse in South Africa. The seedlings were sprayed with paclobutrazol or uniconazole at 0.005–0.4%, with a set of unsprayed seedlings used as controls. All the chemical treatments reduced the extension of the shoots (about 4–12 cm) compared with that in the control plants (about 35 cm), with the greatest response recorded in the seedlings given the highest dose. Overall, uniconazole was more inhibitory than paclobutrazol. Earlier research by these authors showed that paclobutrazol sprayed onto the leaves (0.4%) or injected into the trunk of trees (1.0%) grown in the field reduced shoot growth in spring compared with the growth in control trees (Köhne and Kremer-Köhne, 1987). The effect lasted for at least 40 days.

Köhne and Kremer-Köhne (1991, 1992) examined the effect of paclobutrazol on the growth of young trees planted in South Africa. They compared the growth of trees planted at high density (800 trees per ha) and treated with paclobutrazol with the growth of trees planted at low or standard density (400 trees per ha) and not treated with paclobutrazol. Foliar applications and trunk injections of the growth regulator controlled growth for up to six weeks, while soil drenches controlled growth for up to six months. The trees treated with the growth regulator in the dense planting were smaller than the untreated trees in the standard planting, and were nearly twice as productive over four years (Table 2). The experiment was abandoned after five years due to overcrowding in the closely planted orchard.

Paclobutrazol applied to the leaves in spring or autumn controlled shoot growth in several experiments in South Africa and Australia (Köhne and Kremer-Köhne, 1987; Symons and Wolstenholme, 1990; Thorp and Sedgley, 1993b; Wolstenholme et al., 1990; Whiley et al., 1991). The treated trees sometimes had a higher rate of fruit set compared with the rate in untreated trees, but this response was not always associated with higher yields (Tables 8–10). It is apparent that the effect of paclobutrazol in enhancing fruit growth was sometimes only temporary.

Stassen et al. (1999b) evaluated the effect of paclobutrazol and uniconazole on the growth of avocado in South Africa. The trees were planted at a density of 800 trees per ha and were about four-years old when they were treated. Most of the trees treated with the chemical had similar yields (6.5–7.8 t per ha) as the control trees (6.9 t per ha), with one treatment providing lower yields (4.8 t per ha) than the controls. Leonardi (2008) sprayed prohexadione-calcium on five-year-old 'Hass' trees in Australia. The chemical was applied to the trees twice in September over two years during flowering. The chemical reduced the growth of the spring shoots compared with the growth achieved in untreated trees, but did not affect yield (Table 10).

The effect of paclobutrazol on the performance of 'Fuerte' trees growing in Israel was investigated by Adato (1990). The chemical was applied to the leaves at a rate of 0.5 or 1.0% to 10-year-old trees growing in four orchards. The chemical did not change the timing or the number of growth flushes on the trees compared with the growth observed in the controls, but reduced shoot extension by about 30%. Yields of the treated trees were up to three times the yields of the control trees, with the best response recorded when the trees were sprayed when the inflorescences were elongating or when the flowers were opening. These results were confirmed by a later study in Australia (Thorp and Sedgley, 1993b), where applications of paclobutrazol in spring were more effective in controlling shoot growth than applications in summer, autumn or winter. Increases in yield following applications of paclobutrazol in spring are probably related to a reduction in the competition between the developing fruit and the new shoots (Zilkah et al., 1987; Finazzo et al., 1994).

Research on the response of avocado trees to growth regulators has been fairly active over the past twenty-five years. Most of these investigations have been conducted in South Africa and Australia. Some researchers have been interested in controlling the growth of the trees, whereas others have been interested in manipulating growth in favour of the flowers and fruit. A few researchers have been interested in both ideas. The growth regulators can be applied by several different methods, including foliar sprays, injections into the trunks of the trees and drenches to the soil. Some of the

Table 8
Effect of paclobutrazol on shoot growth and yield of 'Hass' and 'Fuerte' avocado trees in Australia. Data on shoot growth are from non-fruiting branches. Paclobutrazol reduced shoot growth but did not increase yields.

Treatment	Hass		Fuerte	
	Length of spring shoot (cm)	Yield (kg per tree)	Length of spring shoot (cm)	Yield (kg per tree)
Control	192	136	148	110
Paclobutrazol (0.25%)	101	143	87	122
Paclobutrazol (0.5%)	110	139	102	123
Paclobutrazol (0.25%) × 2 in spring	109	113	86	107
Paclobutrazol (0.25%) in spring and summer	119	128	82	123

Adapted from Wolstenholme et al. (1990).

Table 9
Effect of paclobutrazol on shoot growth and yield of 'Hass' avocado trees in Australia. The trees were sprayed with paclobutrazol in 1986, 1987, and 1988. Data are shown for shoot growth in spring 1987 and summer 1988, and accumulated yield from 1987 to 1989. Paclobutrazol had no effect on yield in individual years, but increased cumulative yields.

Treatment	Length of spring shoot (cm)	Length of summer shoot (cm)	Cumulative yield (kg per tree)
Control	154	238	351
Paclobutrazol (0.062%)	98	187	500
Paclobutrazol (0.125%)	79	194	494
Paclobutrazol (0.250%)	85	195	403

Adapted from Whiley et al. (1991).

Table 10
Effect of prohexadione-calcium on shoot growth and yield of 'Hass' avocado trees in Australia. The trees were sprayed twice in September 2004 and 2005. The growth of the spring shoots was measured in December each year. Prohexadione-calcium reduced shoot growth, but did not affect yields.

Treatment	2004/2005		2005/2006	
	Length of spring shoot (cm)	Yield (t per ha)	Length of spring shoot (cm)	Yield (t per ha)
Control	12.3	18.1	12.0	17.0
Prohexadione-calcium (0.005%)	10.4	17.9	10.4	17.9
Prohexadione-calcium (0.008%)	8.9	20.1	8.8	21.1
Prohexadione-calcium (0.010%)	9.1	19.1	8.8	17.1

Adapted from Leonardi (2008).

chemicals have a long life in the tree and the soil, and the doses applied must be carefully managed to avoid long-term stunting of the trees. This is particularly important with applications directly to the soil at the base of the trees.

Chemicals such as paclobutrazol, uniconazole and prohexadione-calcium can reduce the growth of avocado shoots, with the effect generally lasting for at least several weeks. Uniconazole is usually less persistent than paclobutrazol. The effect of the chemicals on fruit set and yield has been less consistent than the effect on shoot growth. There have been many cases where the growth regulators have decreased shoot growth without any subsequent benefit in terms of productivity. There has only been one experiment where there has been an attempt to keep trees planted at high density productive through the use of chemicals (Köhne and Kremer-Köhne, 1991, 1992). The treated trees were initially smaller and more productive than untreated trees grown at low density. However, eventually the experiment was abandoned, possibly because the trees were not pruned.

7. Use of dwarfing rootstocks and scions to control tree growth

It is easier to establish high-density orchards if the trees are naturally small. Dwarfing can be due to the rootstock or the scion, or both. There have been some attempts to develop dwarfing rootstock and a few attempts to develop dwarfing scions. Overall, none of these programmes have resulted in the development of commercial material. Conventional breeding approaches in avocado are slow and expensive because of the long juvenile period for flowering and cropping, and large amount of land required to grow vigorous seedlings (Calderón-Vázquez et al., 2013).

Rootstocks can affect tree growth, yield, disease resistance and fruit quality (Köhne, 1992; Ben-Ya'acov and Michelson, 1995; Bijzet and Sippel, 2001; Wolstenholme, 2003). Research has mainly focused developing material resistant to root rot caused by *P. cinnamomi*, but there has also been some interest in dwarfing (Ben-Ya'acov and Michelson, 1995; Bergh and Whitsell, 1962). Scientists in California, Mexico, Israel, South Africa and Australia have bred or selected rootstocks adapted to different growing conditions. Dwarfing scions can be identified by their small canopies, whereas dwarfing rootstocks can only be identified when they are grafted onto scions (Thorp and Hallett, 1999).

Across different growing areas, Mexican rootstocks are the most important (Wolstenholme, 2003). Commercial rootstocks were initially selected in California, for their tolerance to cold weather and later to root rot. In Israel, West Indian rootstocks were selected for their tolerance to saline soils. 'Duke 7' is a popular rootstock in many growing areas, while the Guatemalan × West Indian 'Velvick' has been successful in the humid tropical areas of Australia (Crane et al., 2013). A recent review on the industry in South Africa indicated that clonal rootstocks accounted for more than 80% of nursery sales (Donkin, 2012). The most popular rootstock is 'Dusa', followed by 'Duke 7' and 'Bounty'. Nearly all the commercial rootstocks around the world are vigorous, a trait which imparts some tolerance to root rot.

Ben-Ya'acov and Michelson (1995) and Thorp and Hallett (1999) discussed strategies for the development of dwarfing rootstocks in avocado. They indicated that seedlings from the West Indian race were more dwarfing than seedlings from the Mexican or Guatemalan races. Certain species, including *Persea schiedeana*, *Persea floccosa* and *P. americana* var. *nubigeana* were considered as possible sources of dwarfing. Preliminary research suggested

Table 11
Effect of seedling rootstocks on the growth and yield of 'Fuerte' and 'Ettinger' avocado trees in Cyprus. The trees were planted in 1971, with yields collected from 1981 to 1990. The circumference of the trunk was recorded in 1990. Rootstock affected the yield of both cultivars but only growth in 'Ettinger'.

Rootstock	Fuerte		Ettinger	
	Trunk surface area (cm^2)	Yield (kg per tree)	Trunk surface area (cm^2)	Yield (kg per tree)
West Indian	397	468	508	619
Duke	320	373	383	337
Topa Topa	363	467	791	567
Mexicola	337	585	289	345

Adapted from Gregoriou (1992).

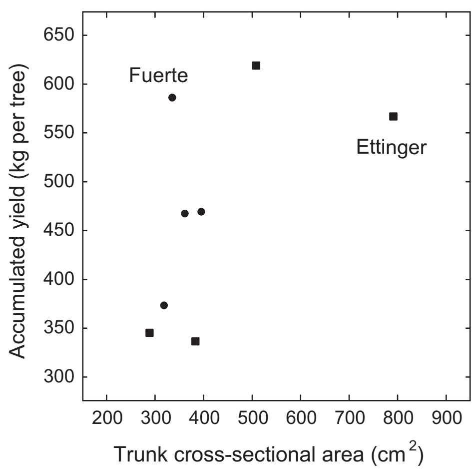

Fig. 6. Relationship between accumulated yield and cross-sectional trunk area in 'Fuerte' (●) and 'Ettinger' (■) avocado trees grown on four seedling rootstocks in Cyprus. The trees were planted in 1971, with yields collected from 1981 to 1990. The cross-sectional area of the trunk was measured in 1990. There was no clear relationship between yield and tree growth. Small trees growing on dwarfing rootstocks had similar yields as large trees growing on standard rootstocks. Small trees growing on dwarfing rootstocks also had low and high yields.
Adapted from Gregoriou (1992).

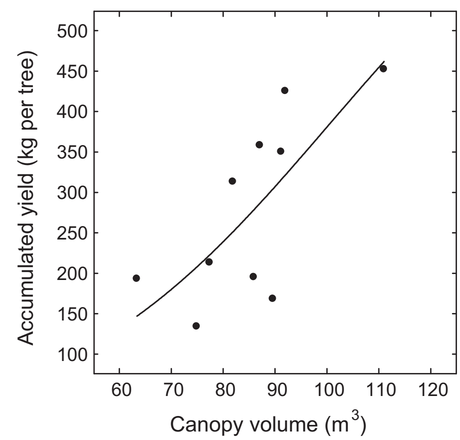

Fig. 7. Relationship between accumulated yield and canopy volume in 'Hass' avocado trees grown on ten clonal rootstocks in California. The trees were planted in 1986, with yields collected over ten years. The canopy volume of each tree was measured in year eight. Yield = 767/{1 + exp[−(canopy volume − 100)/25.7]} (R^2 = 0.40). There was a trend for yield to increase with the size of the canopy, although the data were highly variable.
Adapted from Mickelbart et al. (2007).

that particular characteristics of the stem such as the density of the xylem vessels and the amount of bark might be associated with dwarfing.

Gregoriou (1992) examined the effect of seedling rootstocks on the performance of 'Fuerte' and 'Ettinger' trees growing in Cyprus. The trees were planted in 1971, with yield data collected from 1981 to 1990. The cross-sectional area of the trunk was also measured at the end of the experiment to give some indication of the growth of the trees. The data collected in Cyprus provide an indication of the impact of rootstock on the productivity of trees growing in an area with a Mediterranean climate and a calcareous soil. Rootstock affected the yield of both cultivars (Table 11). In 'Fuerte' the highest accumulated yield was obtained with the 'Mexicola' rootstock, while in 'Ettinger', the highest accumulated yield was obtained with the West Indian rootstock. Average yields pooled across the different rootstocks were similar in the two cultivars. There was a mixed effect of rootstock on the growth of the trees. In 'Fuerte' the trees had similar growth rates as indicated by the growth of the trunk, whereas in 'Ettinger', tree growth was greatest with 'Topa Topa' and least with 'Duke' and 'Mexicola'. There was no clear relationship between accumulated yield and tree growth (Fig. 6), with both small and large canopies producing heavy crops. These results suggest that small trees growing on dwarfing rootstocks can have similar yields as large trees without dwarfing rootstocks.

Mickelbart et al. (2007) conducted a similar experiment as the one in Cyprus using 'Hass' trees in California, but used clonal material rather than seedlings. Ten rootstocks, including the popular 'Duke 7' were evaluated over ten years at a site where the trees had no visible symptoms of root rot. The trees grafted onto 'Borchard' or 'Duke 7' had the highest accumulated yields, with other rootstocks providing intermediate yields, and others lower yields. There were also differences in the size of the canopy under the different rootstocks measured after eight years. Overall, there was trend for yield to increase with the size of the canopy (Fig. 7). However, there was a large scatter in the data, suggesting some rootstocks provided higher yield for the same canopy volume. Mickelbart et al. indicated that yield efficiency ranged from 0.5 to 1.2 kg per m^3 in the different trees. An earlier report by the same group up to year six (Arpaia et al., 1993), found that accumulated yield was weakly related to canopy volume, but not related to the circumference of the trunk or the height of the trees (Fig. 8).

In the early 1950s, a programme was established in California to produce rootstocks that were tolerant or resistant to root rot and tolerant to high salinity levels (Menge et al., 2012). As part of this work, an orchard was established to evaluate dwarfing rootstocks (Bergh and Whitsell, 1962; Douhan, 2011). A seeding named 'MT 4' was small with short internodes and was propagated using embryo sectioning from self-pollinated seed. When this material was used as a rootstock for 'Bacon', the trees were small and precocious (Bergh and Whitsell, 1962). Unfortunately, further testing of this rootstock in California failed to indicate significant dwarfing and it was abandoned (Sauls et al., 1976; Barrientos-Priego et al., 1992; Mickelbart et al., 2007). It became apparent that the method of propagation of 'MT 4' had stunted the roots of the plant and that it was not truly dwarfing. There were other false hopes from Californian such as 'Erin', a 'Duke 9' seedling, that was later found to be susceptible to root rot (Menge, 2004). Despite more than 60 years of effort, no commercial dwarfing rootstocks have emerged from this programme (Douhan, 2011).

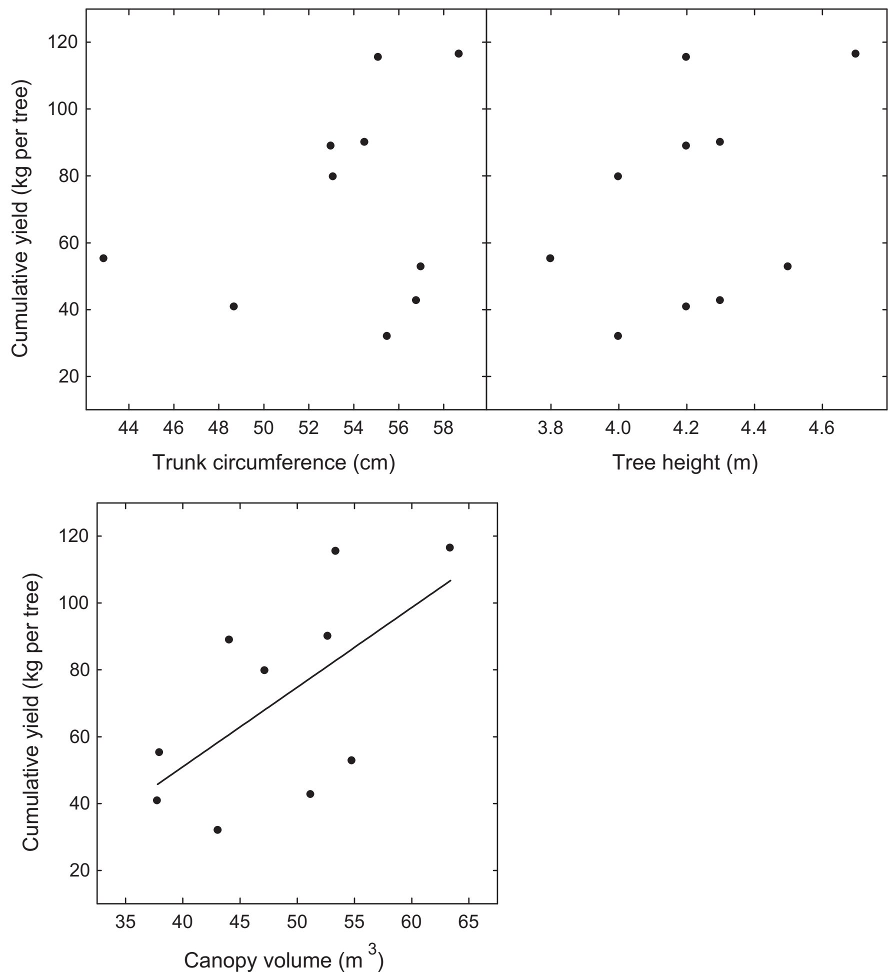

Fig. 8. Relationship between accumulated yield and various indices of growth in 'Hass' avocado trees grown on ten clonal rootstocks in California. The trees were planted in 1986, with yields collected over six years. The growth of each tree was measured in year six. Yield = –44.2 + 2.38 × canopy volume (R^2 = 0.39). Yield was weakly related to the size of the canopy under different rootstocks.

Adapted from Arpaia et al. (1993).

A programme established in 1953 in Mexico produced 'Colin V-33' as a potential dwarfing rootstock (Sanchez-Colin and Barrientos-Priego, 1987). Barrientos-Priego et al. (1992) grew seven cultivars, including 'Hass' on 98 seedling rootstocks of this selection and measured their growth over six years. They presented data on growth of the smallest and largest tree in each cultivar grafted onto the seedlings. For 'Hass', the canopy diameter of the smallest tree at the end of the experiment was only two-thirds of that of the largest tree. The dwarfing effect was not immediate and was most apparent four to seven years after planting. 'Colin V-33' was evaluated in South Africa as a rootstock or interstock, but had mixed effects on dwarfing trees and was never commercialised (Barrientos-Priego et al., 1987; Roe et al., 1995, 1997).

'Moaz' was one of the first dwarfing rootstocks produced in Israel (Ben-Ya'acov and Michelson, 1995). Despite its initial promise, the roots were found to be readily infected with root rot in poorly drained soils and it was abandoned. Other failures included 'Acre', 'Nachlat' and 'Mekler' (Ben-Ya'acov et al., 1993). It was suggested that individual rootstocks may perform differently under different growing conditions and may not dwarf all scions. For example, 'Ashdot' produced vigorous trees and provided poor yields in Israel (Ben-Ya'acov et al., 1993). However, it dwarfed 'Hass' and provided good yields under good growing conditions in Australia (Le Lagadec, 2010). Ben-Ya'acov and Michelson (1995) postulated that dwarfing is sometimes associated with poor root development, and poor water and nutrient uptake. Overall yields of 'Hass' trees grafted onto different rootstocks in several orchards in Israel were related to the growth of the trees, whereas the relationships in 'Ettinger' and 'Fuerte' were fairly weak (Ben-Ya'acov, 1975).

Two programmes were established in the 1980s in South Africa to evaluate rootstocks that were tolerant to root rot and were dwarfing (Burger, 1985; Kremer-Köhne et al., 2011). 'Barr Duke' was identified as a possible candidate (Sippel et al., 1995) but was not released. 'Wilg' was another potential dwarfing release. 'Hass' trees grafted on to this rootstock were initially small and precocious (Roe et al., 1995). However in the second year, the trees produced no crop and thereafter, yielded less than the control trees grafted onto 'Duke 7' (Roe et al., 1997). By the fifth year, the trees on 'Wilg' were as large as the controls (Roe and Morudu, 2000). This rootstock was never commercialised in South Africa or elsewhere.

Dwarfing rootstocks have shallow roots and do not tolerate poorly-drained soils, droughts or low fertility (Ben-Ya'acov and Michelson, 1995). This may be why dwarfing rootstocks have not been commercialised. The rootstocks that were thought to be dwarfing may simply have been stunted due to poor growing conditions, poor husbandry or their susceptibility to root rot. Since most avocado trees naturally grow into large specimens and are vigorous, the quest to find dwarfing rootstocks will require considerable effort.

No true dwarfing trees (scions) have been released for commercial cultivation. Tree form varies considerable across the present genepool from erect as in 'Reed' to spreading as in 'Fuerte' and weeping as in 'Wurtz'. Plant breeders consider a spread about equal to the height of the trees desirable (Lahav and Lavi, 2013). Very tall cultivars such as Bacon and Ettinger are more difficult to manage and harvest than smaller cultivars. High yields are not necessarily associated with vigorous tree growth.

'Hass' is the main cultivar in the world, and the most important cultivar in the export market, accounting for more than 90% of the trade (Crane et al., 2013). It was selected in California in the 1920s, and is a medium to large tree, with a semi-upright growth habit, and is almost as broad as it is tall with a rounded crown. In Mexico, the leading country in world production, 90% of commercial orchards are comprised of 'Hass' (Bayram et al., 2012). 'Fuerte' is one of the other important cultivars, although plantings are less significant compared with those of 'Hass'. This cultivar was selected in Mexico more than 100 years ago. The trees are large, with spreading crowns.

Other important cultivars produced in different growing areas, include Bacon and Ettinger (upright trees as indicated above), Edranol (upright vigorous growth habit), various Hass selections with more compact trees than traditional Hass, Pinkerton (semi-dwarf, moderately spreading tree), Ryan (medium to large spreading tree), Sharwil (large tree with a broad crown), Shepard (semi-dwarf tree with a compact growth habit), and Zutano (semi-dwarf with a sprawling growth habit). The development of new avocado cultivars has been relatively slow, with only two significant cultivars (Hass and Fuerte) selected in the past 100 years or so. Crane et al. (2013) indicated that breeding is still active in several countries. Hopefully, some of the new material released over the next few years will include trees with a dwarfing or semi-dwarfing growth habit.

There has been considerable investment in the search for dwarfing rootstocks in avocado. Research has been active in South Africa, Israel, California, Mexico and other places. Several dwarfing rootstocks have been released over the past 20 years. However, their performance has been highly variable and generally disappointing when assessed in different growing areas. At this stage, no dwarfing rootstock has been commercialised. Most of the research in avocado has concentrated on developing rootstocks that are resistant to root rot (Menge et al., 2012). It is generally felt that these rootstocks do not have any dwarfing effect.

Commercial avocado production around the world is primarily based on the two cultivars Hass and Fuerte that were developed nearly 100 years ago. There are several breeding programmes in California, Mexico, South Africa and Israel developing new cultivars, but no true dwarf cultivars have been produced that are suitable for intensive production on a wide scale. Avocados growing naturally in central America are large trees, with some specimens growing to heights of 15–18 m or more. It could be some time before small trees that can produce large quantities of fruit, similar to the quality of the popular 'Hass' are developed or selected.

8. Planting systems used in new orchards

Hofshi (1999a,b,c) described the development of high-density orchards planted in California. Small experimental orchards of 'Lamb Hass' and 'Reed' were established at 1973 trees per ha. The trees were heavily pruned each year, mostly after the following year's crop had been set. The trees were kept small so that the crop could be harvested by hand. This reduced harvesting costs and allowed for the easy application of pesticides. The intensive pruning also improved the distribution of light through the canopy. Productivity was very high and up to 82 t per ha after six years. This was about two to three times the yields of traditional plantings. These high-density plantings were suited to cultivars with a strong dominant trunk such as 'Gwen', 'Lamb Hass' and 'Reed'. However, these cultivars only represent a small proportion of the avocado plantings in California, which are still dominated by 'Hass'. There has been no economic analysis of this technology in California.

Gardiazabal and Mena (2011) described the development of high-density 'Hass' plantings in Chile. The trees are planted at densities of 1100 trees per ha or higher at a distance of 3 m or less on very steep slopes. The first orchards were planted in 2004, with more than 3500 ha now under intensive production. These authors reported on the productivity of two orchards planted in 2004 or 2006 and monitored for six or seven years (Fig. 9). Production on a per hectare basis was high, except for one of the orchards in one year where the trees temporarily became over-crowded and shaded due to a lack of pruning soon after planting. The success of the high-density plantings in Chile is related the soils and climate of the area which restrict the growth of the trees. For instance, it is much cooler in this area than in California, and the soils are relatively shallow (30–100 cm deep). Most of the rain falls in winter when growth is relatively slow. The trees are grown as individual plantings, with no access for machinery along the narrow inter-rows. The trees are initially pruned to develop an acceptable shape, and then pruned on a regular basis to maintain tree height and improve light distribution through the canopy.

Plant growth regulators have played a significant role in this production system in Chile. Some trees in mature orchards have become stunted due to the accumulation of these chemicals in the soil. There are also possible problems with residues in the fruit. Several studies have shown that paclobutrazol can persist in the soil, and may contaminate ground waters (Sharma and Awasthi, 2005; Shalini and Sharma, 2006; Wu et al., 2013). Gardiazabal et al. (1995) did not detect any residues in the harvested fruit when the trees were sprayed with paclobutrazol in March and/or October in their study with two-year-old trees. Foliar sprays are less likely to accumulate in the fruit and soil than soil drenches. Research on high-density plantings is continuing in Chile (Bonino et al., 2011). Whether this work is applicable to other growing environments is unknown.

9. Future directions

Avocado trees grow into large specimens and can remain high yielding for many years after planting. However, eventually the lower branches become heavily shaded, and production declines. There can also be problems harvesting such large trees and applying chemicals for the control of pests and diseases. Most commercial orchards continue to be planted at relatively low densities. Research has shown that these orchards take a long time to recover the initial costs of planting and establishment compared with the time taken when trees are planted at high densities. However, the problems of over-crowding and shading occur earlier in these close plantings, in the absence of effective canopy management. Most of the research on high-density plantings was conducted in the 1990s, with few reports published after this time.

The development of close plantings in avocado is dependent on the production of small trees that have high rates of light interception and distribution though the canopy. There is a range in the growth rate of existing avocado cultivars, but none of the current ones are naturally small or dwarfing. The development of dwarfing rootstocks has been largely unsuccessful. Other methods have been suggested to control the growth of the trees and to maintain production in established orchards. These include the application of growth regulators, and intensive canopy management.

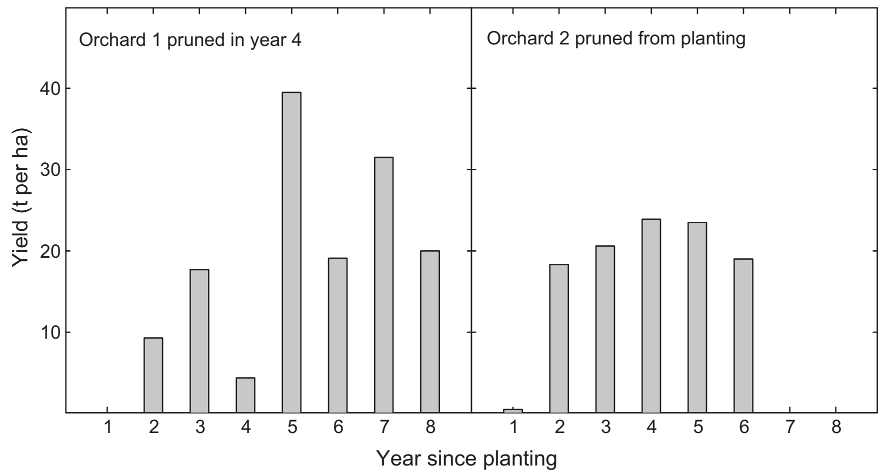

Fig. 9. Yields of 'Hass' avocado trees grown at 1100 trees per ha in Chile. The trees in the first orchard were planted in 2004 and yields collected from 2006 to 2012. The trees in the second orchard were planted in 2006 and yields collected from 2007 to 2012. Productivity in 2012 was estimated. The trees in the first orchard became over-crowded and were pruned in year 4, whereas the trees in the second orchard were pruned from planting. Yields in the dense orchards were relatively stable as long as the trees were pruned regularly.

Adapted from Gardiazabal and Mena (2011).

Köhne and Kremer-Köhne (1991) examined the use of paclobutrazol to control the growth of 'Hass' trees planted at high density in South Africa. The chemical controlled growth for up to six months. The trees treated with the growth regulator were smaller than the trees in the standard planting, and were nearly twice as productive over the four years of cropping. None of the trees in this experiment were pruned, and the research was eventually abandoned because the investigators were unable to control the growth of the trees. Further studies should be initiated to examine whether the application of growth regulators combined with intensive canopy management can maintain the life of high-density plantings.

This research needs to take into account the need to minimise residues of the chemicals in the marketed fruit. There are some restrictions on the use of paclobutrazol and uniconazole because of concerns about residues in the pulp. There is a range in the accepted minimum residue limits (MRLs) for these two chemicals in different countries, which can be as low as 0.01 mg per kg and up to 0.1 mg per kg or higher. Some authorities accept a period of three months between application of paclobutrazol and harvest of the fruit, while in other places the recommended gap is six months. This can be a challenge in cool climates where successive crops may overlap.

Several authors have investigated the effect of pruning on the productivity of avocado orchards. The results of some of these studies have shown that productivity can be maintained if the trees are not pruned too severely or pruned at the wrong time. For instance, Leonardi (2005) found that productivity in subtropical Australia could be maintained if the trees were pruned lightly after harvest and again in September. Experiments should be set up using some of the principles developed by Leonardi and others to determine whether annual pruning can control the growth of high-density orchards without significantly reducing productivity. Later studies could investigate the optimum shape and size of the trees, similar to the work conducted in olive by Connor et al. (2014). Further studies need to be conducted to determine the relationship between yield and canopy volume in different growing systems.

10. Conclusions

There have been numerous attempts to grow avocados in close plantings. However, apart from a few areas in Chile and California, these efforts have been largely unsuccessful. Most of the experiments were abandoned after five or six years because the trees started to crowd out each other. Avocado trees are naturally vigorous. Efforts to prune the trees to keep them small often have come at the expense of productivity. The development of high-density plantings in this crop is dependent on the production of dwarfing rootstocks and more reliable methods of canopy management. High-density orchards do not appear viable in the short term.

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