THE WATER RELATIONS AND IRRIGATION REQUIREMENTS OF AVOCADO (*Persea americana* Mill.): A REVIEW

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SUMMARY

The results of research on the water relations and irrigation need of avocado are collated and reviewed in an attempt to link fundamental studies on crop physiology to irrigation practices. Background information is given on the centre of origin (Mexico and Central America) and the three distinct ecological areas where avocados are grown commercially: (1) Cool, semi-arid climates with winter-dominant rainfall (e.g. Southern California, Chile, Israel); (2) Humid, subtropical climates with summer-dominant rainfall (e.g. eastern Australia, Mexico, South Africa); and (3) Tropical or semi-tropical climates also with summer-dominant rainfall (e.g. Brazil, Florida and Indonesia). Most of the research reported has been done in Australia, California, Israel and South Africa. There are three ecological races that are given varietal status within the species: *Persea americana* var. *drymifolia* (Mexican race), *P. americana* var. *guatemalensis* (Guatemalan race) and *P. americana* var. *americana* (Antillean, West Indian or Lowland race). Interracial crossing has taken place. This paper summarises the effects of water deficits on the development processes of the crop and then reviews plant–water relations, crop water requirements, water productivity and irrigation systems. Shoot growth in mature trees is synchronised into flushes. Flower initiation occurs in the autumn, with flowering in late winter and spring. Flowers form on the ends of the branches. A large heavily flowering tree may have over a million flowers, but only produce 200–300 fruits. Fruit load adjustment occurs by shedding during the first three to four weeks after fruit set and again in early summer. Water deficits during critical stages of fruit ontogeny have been linked to fruit disorders such as ring-neck. Reproductive growth is very resistant to water stress (compared with vegetative growth). Avocado is conventionally considered to be shallow rooted, although roots extend to depths greater than 1.5 m. The majority of feeder roots are found in the top 0.60 m of soil and root extension can continue throughout the year. Leaves develop a waxy cuticle on both surfaces, which is interrupted by stomata on the abaxial surface ($350–510$ mm^{-2}), many of which are blocked by wax. Stomata are also present on the sepals and petals at low densities (and on young fruit). During flowering, the canopy surface area available for water loss is considerably increased. Stomatal closure is an early indicator of water stress, which together with associated changes in leaf anatomy, restricts CO_2 diffusion. There have only been a few attempts to measure the actual water use of avocado trees. In Mediterranean-type climates, peak rates of water use (in summer) appear to be between 3 and 5 mm d^{-1}. For mature trees, the crop coefficient (K_c) is usually within the range 0.4–0.6. The best estimate of water productivity is between 1 and 2 kg fruit m^{-3}. Soil flooding and the resultant reduction in oxygen level can damage roots even in the absence of root rot. Avocado is particularly sensitive to salinity, notably that caused by chloride ions. Rootstocks vary in their sensitivity. Both drip and under-tree microsprinklers have been/are successfully used to irrigate avocado trees. Mulching of young trees is a recommended water conservation measure and has other benefits. A large proportion of the research reviewed has been published in the 'grey' literature as conference papers and annual reports. Sometimes, this is at the expense of reporting the science on which the recommendations are based in peer-reviewed papers. The pressures on irrigators to improve water productivity are considered.

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INTRODUCTION

The avocado is a fruit of Central America and Mexico, where it has been a staple dietary component for the indigenous people for at least 9000 years. For the rest of the world, it is a relatively new fruit. The centre of diversification is thought to encompass the rainforests of the subtropical to tropical highland areas of Mexico, Guatemala and Honduras and probably extending to Pacific coastal Costa Rica. This area includes habitats ranging from sea level to altitudes in excess of 3000 m with an associated diversity of climates. This has resulted in genetic diversity and adaptability to warm subtropical areas as well as the tropical highlands and humid tropics (Knight and Campbell, 1999; Whiley *et al.*, 2002).

The first commercial orchards were planted in the early 1900s in California, where much of the pioneering research was undertaken. There are now about 25 000 ha grown along the Californian coast and inland about 60 km (Faber, 2006). In Australia, the avocado industry extends from latitude 17°S to 35°S with conditions varying from wet summers and dry springs (east) to hot dry summers and cool wet winters (west) (Turner *et al.*, 2001). In semi-arid climates such as those found in California, Chile, Israel and Australia irrigation is essential. In other areas, irrigation is supplementary. However, in the humid, summer-rainfall subtropics of Florida, Australia and South Africa and in parts of the humid tropics such as Mexico, Brazil and Indonesia unirrigated farming systems can be successful. Although national average yields of fresh fruit are low (< 10 t ha^{-1}), good growers in the semi-arid, winter-rainfall subtropics can obtain 12–15 t ha^{-1} and, in the humid, summer-rainfall subtropics, the best can achieve up to 20–25 t ha^{-1}. A target yield of 30 t ha^{-1} from existing genotypes is considered to be realistic (Wolstenholme and Whiley, 1995). In 2009, the principal producing countries were Mexico (with about 30% of the world total of 3 million t), followed by Chile, USA, Indonesia, Dominican Republic, Colombia, Peru, Brazil and China (FAOSTAT, 2011). Avocados are grown as far north as the Black Sea coast (40°N) and as far south as New Zealand (40°S) on a range of soil types (Partridge, 1997; Wolstenholme, 2002).

Because of its importance internationally, the water relations of the avocado have been the main focus of research, particularly in semi-arid areas. This paper attempts to synthesise this research from an independent perspective, and to do so in practically useful ways. It follows the format used in previous reviews in this series, including other plantation crops grown for their fruit, notably coffee (Carr, 2001), banana (Carr, 2009), coconut (Carr, 2011a), cocoa (Carr and Lockwood, 2011), oil palm (Carr, 2011b) and *Citrus* spp. (Carr, 2012). It begins with a description of the stages of crop development (including roots) in relation to water availability, followed by reviews of plant–water relations, water requirements and water productivity, and irrigation systems. The avocado is one of the best understood of the subtropical/tropical fruit crops as illustrated by the comprehensive book edited by Whiley *et al.* (2002) within which the irrigation of avocado is summarised by Lahav and Whiley (2002).

CROP DEVELOPMENT

Races

There are three ecological races of avocado that are given varietal status within the species: *Persea americana* var. *drymifolia* (Mexican race), *P. americana* var. *guatemalensis* (Guatemalan race) and *P. americana* var. *americana* (Antillean, West Indian or Lowland race). These differ in their relative cold tolerance with the Mexican race being the most cold tolerant and the Antillean the least. Interracial crossing has taken place to such a degree that the most economically important cultivars in both subtropical and tropical areas are the result of hybridisation between races, for example cv. Fuerte (a Mexican × Guatemalan hybrid originating in Mexico, which for many years led the world in commercial production) and cv. Hass (developed and selected in California, and which has now displaced Fuerte in most places that have a Mediterranean-type climate) (Knight, 2002; Knight and Campbell, 1999). The Mexican and Guatemalan ecotypes are both indigenous to the elevated montane forests or 'tropical highlands' where, predominantly, summer and autumn rain is followed by a dry winter and spring, which is when flowering occurs. Both these races, to varying degrees, are also adapted to many warm and cool subtropical areas.

Vegetative growth

The tree is evergreen, (although strictly it is classified as winter-green because the longevity of the leaves is not more than 12 months and the entire leaf canopy is replaced during the renewal spring growth that comes after flowering), with a monopodial trunk up to 20 m tall. All the branches are also monopodial and therefore indeterminate, ending in a vegetative bud. Shoot growth in mature trees is synchronised into flushes of varying vigour, duration and extent. This synchronous growth pattern is marked during the quiescent period by shorter internodes and a ring of closely spaced buds. Leaves expand to full size in about 30 days, and last for 10–12 months (Scora *et al.*, 2002).

The avocado tree has a vegetative bias, resulting in a preferential allocation of assimilates to shoot growth rather than to reproductive organs. This bias, coupled with the relatively short life of the leaves (for a subtropical fruit tree species) results in the rapid production of leaves and increased shading within the canopy, which reduces the number of well-lit terminal shoots capable of flowering. However, except in the spring when shoot growth is synchronised by flowering, not all of a tree flushes at the same time. As a result much of the canopy remains well lit. Young leaves are sinks for photoassimilates for about their first 40 days (Schaffer and Whiley, 2003).

The sensitivity of tree growth to water availability was illustrated in one of the first irrigation experiments with avocado, undertaken in California by Richards *et al.* (1962). Wind damage prevented fruit yields from being recorded, but tree growth (trunk diameter) increased (over the six years of the experiment, 1956 to 1961) the faster the more frequently the soil was irrigated (the quantity of water applied probably also varied). Tensiometers and resistance blocks were used to schedule irrigation in order to maintain soil water potentials in the three treatments above −0.05

(wettest), −0.1 and −1.0 MPa (driest) at depths of 0.30 m. There was a cumulative increase in the diameter of the trunk over time.

Flowering

In subtropical areas, flower initiation occurs during the autumn when shoot growth enters a long-quiescent phase. Flowering occurs during late winter and spring with anthesis spread over a three-to-eight-week period (Whiley and Schaffer, 1994). Inflorescences are panicles of cymes (strictly determinate thyrse with branches terminating in flowers). The inflorescence can either be functionally determinate (where the terminal vegetative bud aborts) or functionally indeterminate (where the bud grows and competes with the developing fruits) (Scora *et al.*, 2002).

Avocados are protogynous (a flower in which the stigma is receptive before the pollen is shed from the anthers of the same flower) and exhibit synchronous dichogamy (anthers and stigmas mature at different times) in which flowers open on the first day when the pistil is receptive and then close and open again on the second day when the pollen is shed and the pistil is no longer receptive. Cultivars vary in the time of opening and closing of the flowers (Purseglove, 1968). Cool conditions during anthesis can influence the periodicity of this process, affecting the need or otherwise for cross-pollination (achieved by interplanting cultivars which differ in the timing of the opening and closing of the flowers).

A large heavily flowering tree may have one to two million flowers, but produce up to 200–300 fruits only. During flowering, as some of the floral parts have stomata (see below), the canopy surface area available for water loss is increased by an estimated *c.* 90% (Whiley *et al.*, 1988).

Fruiting

Under favourable conditions, more fruits are set than the trees can support. In subtropical climates, fruit load adjustment is characterised by shedding during the first three to four weeks after fruit set and again in early summer (Schaffer and Whiley, 2002).

The fruit is botanically a berry with a thick, fleshy mesocarp surrounding a single large seed. It is renowned for its nutritive value. The oil is used by the pharmaceutical industry. The avocado is unusual in that cell division continues, albeit at a slower rate, for as long as the fruit remains on the tree. Differences in fruit size appear to result from cell number as well as cell size. Sound fruits will not ripen whilst held on the tree (Scora *et al.*, 2002). Water deficits during critical stages of fruit ontogeny have been linked to fruit disorders such as ring-neck, in which corky lesions develop at the abscission sites on the fruit stalk, elongated fruits (cv. Hass) and reductions in the internal fruit quality (Schaffer and Whiley, 2002).

Immediately after flowering, many fruits drop from the tree. This is one of the most critical periods determining both yield and fruit size. There is competition for resources between developing fruit and new shoot growth at a time when net assimilation rates and root growth are depressed. In warm humid subtropical climates, assimilates from

current photosynthesis, as opposed to stored sources, are critical for fruit retention and growth (Whiley *et al.*, 1995).

In a series of container experiments in Australia, Turner *et al.* (2001) found that reproductive growth was very resistant to water deficits. Young fruit continued to grow whilst vegetative growth was reduced. Watering only half the root system maintained vegetative and reproductive growth up to fruit set, but drying the root zone wholly or partially for several months caused fruit drop (cv. Hass) (Neuhaus *et al.*, 2007). The avocado is not considered to be drought tolerant (Whiley and Schaffer, 1994).

Roots

The root systems of avocado trees were described by Colt (1940) in California as being relatively shallow, with fine fibrous rootlets in greatest abundance at or near the surface of the soil. These roots were thought to function best when protected by moist, undisturbed leaf mulch, as in their native or wild habitat in the forests of Central America. Subsequently, there have been several attempts to quantify some of these observations.

Depth and distribution: The roots of mature trees (cv. Fuerte) were excavated at two (irrigated with basins) sites in Mexico by Salazar-Garcia and Cortés-Flores (1986). On the sandy loam soil (alt. 1800 m), roots reached depths of 1.4 m, with 43% of all the roots by dry mass in the top 0.2 m and 65% in the top 0.6 m. The horizontal spread was 3 m. By contrast, on the clay soil (alt. 1300 m), the maximum depth of rooting was about 1.2 m, with 21% in the surface 0.2 m and 83% in the top 0.6 m. The horizontal spread was up to 2.5 m. The total dry mass of roots was nearly four times greater in the sandy loam soil than in the clay loam soil.

In South Africa, Durand and Claassens (1987) excavated roots of 18-year-old trees (irrigated) to depths of 1.1 m (the limit of measurement) and as far as 6 m laterally from the trunk. Root distribution (by dry mass) varied with the health of the tree (some were affected by root rot), but in healthy trees, it was fairly uniform vertically and horizontally. They cited other observations of roots being relatively evenly distributed to depths of 1.2 and 2.1 m in deep uniform soils, with some roots even reaching 3.3 m, but with the main concentration being in the top 1.5 m.

Salgado and Toro (1995) originally summarised the results of a detailed study in central Chile of the changes over time in the spatial distribution of 'active' roots (white, $\leq$ 2 mm in diameter) of mature trees (cv. Hass grafted on to Mexicola seeding rootstocks, 12-years-old), as influenced by the method of irrigation (drip and microsprinkler) on two soil types (clay loam and sandy loam). Subsequently, Salgado and Cautin (2008) reported the experiment in full. The density of roots, as observed on trench walls (0.75 m deep × 3.0 m wide) in the autumn was twice that observed at other times of the year under drip irrigation and three times that with microsprinklers. The roots were mainly found in the surface layers (0–0.25 m). Of secondary importance was the observation that there were 25% more roots in the clay loam soil compared with the sandy loam soil, and 30% more roots under drip irrigation than microsprinklers.

Both of these observations were influenced by the large number of roots present in the fine soil-drip irrigation combination. Overall, the highest root frequency was within one metre from the trunk.

In a comparison of two levels of drip irrigation in Israel, Cantuarias *et al.* (1995) observed roots on the sides of an excavated trench in May and June (the period of maximum root activity). Analysis of root distribution with depth from the soil surface indicated that 69% (single drip line) and 80% (five drip lines) of the total root number (in a 1.0-m deep profile) were concentrated in the top 0.36 m.

Neuhaus *et al.* (2009) summarised the results of observations of the root systems of 15-year-old trees (cv. Hass on Guatemalan seedling rootstocks) in which irrigation had been withheld for six months. On a sandy soil in Western Australia, there was no effect on root length density down to 1.3 m from the soil surface. However, the extended drying reduced the length of roots adjacent to the soil surface from 2.1 ± 1.5 to 0.8 ± 0.4 m m^{-2}.

Root extension: In Florida, Ploetz *et al.* (1993) measured rates of extension of shoots and roots (recorded in a rhizotron) over one year for two cultivars (Simmonds and Lula, both grafted onto Waldin seedling rootstocks). Peaks of shoot and root growth occurred in alternating flushes on 30- to 60-day cycles. Although shoot extension ceased during late autumn and winter, root extension continued throughout the year.

Summary: crop development
1. There is considerable genetic diversity within the species and adaptability to warm subtropical areas as well as to the tropical highlands and humid tropics.
2. The tree is evergreen, with a monopodal trunk up to 20 m tall. Shoot growth is synchronised into flushes. Leaves are relatively short lived.
3. Tree growth is very sensitive to water availability.
4. Flower initiation occurs in the autumn, with flowering in late winter and spring.
5. Since flowers form on the terminal ends of branches, avocado trees need to expand each year in order to remain productive.
6. A large heavily flowering tree may have over a million flowers, but produce only 200–300 fruits.
7. Fruit load adjustment is characterised by shedding during the first three to four weeks after fruit set and again in early summer.
8. Differences in fruit size appear to result from cell number rather as well as cell size.
9. Water deficits during critical stages of fruit ontogeny have been linked to fruit disorders such as ring-neck.
10. Reproductive growth is very resistant to water deficits (compared with vegetative growth).
11. Avocado trees are conventionally considered to be shallow rooted, although roots extend to depths greater than 1.5 m (even down to 3.3 m), and laterally up to 3 m (even 6 m).

12. The majority of white unsuberised feeder roots are found in the top 0.60 m of soil. They grow into the decomposing litter layer. Avocado roots have few or no root hairs.
13. Peaks of shoot and root growth occur in alternating flushes.
14. Although shoot extension ceases during late autumn and winter, root extension can continue throughout the year, with an autumn peak.

PLANT−WATER RELATIONS

Stomata

In a detailed study using a scanning electron microscope and porometry, Blanke and Lovatt (1993) examined the structure and functions of the inflorescences of cvs. Hass and Fuerte. A similar study was also undertaken by Whiley *et al.* (1988). Leaves develop a waxy cuticle on both surfaces. Before this waxy layer is formed the young leaves, and the sepals and petals, are densely pubescent, creating an effective boundary layer. Stomata occur on the abaxial surface of the leaves (350–510 mm^{-2}) and are also present on the abaxial surfaces of the sepals and petals at low densities (*c.* 3 mm^{-2}) and on young fruit (50–75 mm^{-2}). The fruits are covered by a waxy film on the surface of the exocarp, which is interrupted by stomata when young but these become plugged and less active with age. The floral stomata appeared to be functional whereas 80% of the stomata found on old leaves were closed. As a result, the transpiration rate per unit area of sepal/petal exceeded that from leaves, whilst transpiration from young fruits exceeded both. Since, during flowering, there are up to two million transpiring flowers with an estimated surface area of 54 m^2 in the periphery of the tree (Blanke and Lovatt, 1993), their contribution to the total water use of a tree is considerable, around 13% according to Whiley *et al.* (1988). These features, together with physiological adjustment in response to soil and atmospheric water deficit (stomatal conductance declines with increases in the saturation deficit of the air (Schaffer and Whiley, 2002)), contribute to the adaptability of avocado to climates as diverse as humid and semi-arid (Scora *et al.*, 2002).

In Mexico, Barrientos Priego and Sanchez Colin (1987) compared the stomatal densities of a selection of cultivars with different growth habits, which included dwarf mutants. There was nearly a four-fold difference in densities (units not specified) between the extremes, with the trend of increasing stomatal density with reductions in tree height. Stomatal density in cv. Fuerte, included as a standard, was intermediate.

In a series of experiments in Australia, designed to answer fundamental questions about the physiology of the avocado and linking that to yield and water productivity, Turner *et al.* (2001) found (surprisingly) that water deficits caused the stomata to close (and transpiration to cease) before any other changes, including leaf and young fruit expansion, were detected. Diurnal fluctuations in fruit diameter are proportionally greater in young fruit (Schaffer and Whiley, 2002). Citing others, particularly Neuhaus (2003), Schaffer and Whiley (2003) stated that stomatal conductance is a more reliable early indicator of a water deficit in avocados than measurements of leaf water content, leaf water potential or growth variables. Stomatal conductance begins to decline when

the leaf water potential falls below -0.4 MPa, and continues to decline until it reaches -1.0 to -1.2 MPa, when the stomata are fully closed. This decline is accompanied by a parallel reduction in net photosynthesis.

From a series of (not very convincing) field measurements of plant–water status made in Israel on an irrigated crop (cv. Hass), Sharon (1999) and Sharon *et al.* (2001) confirmed the sensitivity of trunk and leaf contractions to diurnal changes in leaf water potential (diurnal range -0.15 to -1.05 MPa). They also showed how the stomata remained open during the day (even at 36 °C). The capacity of avocado trees to maintain fast rates of transpiration was attributed to a high root hydraulic conductivity (compared with *Citrus* spp.).

Photosynthesis

Being an under storey highland rainforest species, the avocado is shade tolerant and has an adaptive advantage in colonising small gaps when the forest canopy is disturbed (Schaffer and Whiley, 2002). Light saturation of mature leaves of field grown trees (cv. Hass) occurs at a photon flux density (PPF) of 1100 μmol m^{-2} s^{-1}. This is about half the PPF in full sun at midday at low- to mid latitudes.

In a detailed, well-reported study, Chartzoulakis *et al.* (2002) compared the responses of two cultivars (Fuerte and Hass) to a moderate water deficit over a six-month period. Avocado plants, two-years-old, were grown in pots outdoors in Crete (Greece). Water deficit-induced changes in leaf anatomy were observed in both cultivars. These included reductions in the thickness of (most of) the histological components of the mesophyll. The resultant 35–45% reduction in leaf porosity restricted rates of carbon dioxide (CO_2) diffusion to the chloroplasts within the leaf, and lowered the internal CO_2 concentrations. Water deficits also resulted in concurrent reductions in stomatal conductance. As a result of both these water deficit-induced processes, photosynthesis rates were reduced. Drought also reduced the osmotic potential, mainly as a result of dehydration (rather than through active solute accumulation) and, in particular, increased tissue elasticity in both cultivars. By doing so, the pressure potential (turgor pressure) was maintained. Growth data suggested that cv. Hass was more productive than cv. Fuerte under well-watered conditions, but was more susceptible to water deficits.

Transpiration

Under conditions of high evaporative demand ($ET_o = 7$–15 mm d^{-1}) in the northern Negev, Israel, actual transpiration (T, based on sap flow measurements) on trees well supplied with water reached a maximum of only 3 mm d^{-1}. The ratio T/ET_o was low and remained in the range 0.13–0.21. For irrigated, 14-year-old avocado trees (cv. Ettinger), leaf water potentials stayed relatively constant ($c.$ -0.5 MPa for sunlit leaves). The same experiment showed that enlargement of the wetted soil volume from 25 to 75% improved tree water status and transpiration rates as well as root growth (Cantuarias *et al.*, 1995).

Xylem vessels

Differences exist between the races and genotypes in the susceptibility of the xylem vessels to cavitation when under water stress. In a comparison of relative vulnerability (to cavitation), Reyes-Santamaría *et al.* (2002) found that the three avocado races had higher vessel frequencies (20–22 vessels mm^{-2}) than the two cultivars (Fuerte and Hass *c.* 12 vessels mm^{-2}), but smaller vessel diameters (races 99–107 μm; cultivars 116–117 μm). In terms of the vulnerability index (= vessel diameter/frequency), the two cultivars had the highest values whilst the races had the lowest. It was concluded that the races were less susceptible to hydraulic failure than the cultivars and that within the races the Guatemalan was better adapted to water deficits than the Mexican or Antillean races. A dwarf genotype had characteristics intermediate between the three races and the two cultivars.

The choice of an appropriate rootstock is important not only for optimising tree growth and productivity but also for reducing water consumption. In a glasshouse experiment in California, Fassio *et al.* (2009) related sap flow rates to the xylem anatomy of two clones (Duke 7 and Toro Canyon) and two composites (Hass scion grafted on to Duke 7 and Toro Canyon rootstocks). Duke 7 had a 29% higher flow rate (transpiration) than Toro Canyon whether or not it was grafted. There were no differences in the xylem vessel features in the stems of any of the cultivars. However, the roots of Duke 7 had wider and fewer vessels than Toro Canyon, as well as a 19% larger total vessel area, suggesting that the differences in water consumption of Hass on different rootstocks may be linked to differences in the efficiency of the conductive tissue in the root.

In Australia, the xylem vessels of droughted avocado plants were observed to contain tyloses (outgrowths into the xylem lumen). Even 84 days after re-watering up to 34% of the vessels remained occluded by tyloses. Fluorescent dyes showed that these restricted water flow in the stems as a result of a 50% reduction in hydraulic conductivity. Restrictions to water flow in the leaf petiole were caused by embolisms/cavitation. In well-watered trees, or those subjected to drought on only one side of the trunk, no tyloses were found in the xylem vessels (Turner *et al.*, 2001; Neuhaus *et al.* 2007).

Summary: plant–water relations

1. Young leaves (and the sepals and petals) are densely pubescent, creating an effective boundary layer.
2. Leaves develop a waxy cuticle on both surfaces, which is interrupted by stomata on the abaxial surface (350–510 mm^{-2}), many of which are blocked.
3. Stomata are also present on the sepals and petals at low densities (and on young fruit).
4. During flowering, the canopy surface area available for water loss is considerably increased.
5. Stomatal closure is an early indicator of water stress.
6. The avocado tree is shade tolerant.

7. Water deficits induce changes in leaf anatomy resulting in a reduction in leaf porosity, which restricts CO_2 diffusion.
8. Even when the potential evapotranspiration (ET_o) rates are large (7–15 mm d^{-1}), the maximum rate of transpiration measured was only 3 mm d^{-1}. The ratio T/ET_o was always small (0.13–0.21).
9. Leaf water potentials remained constant (−0.5 MPa) over the same range of ET_o values.
10. Differences exist between the races and genotypes in the susceptibility of the xylem vessels to cavitation when under water stress.
11. Differences in water use by cv. Hass on different rootstocks may be linked to the conductivity of the rootstock.
12. Droughted plants develop tyloses in the xylem vessels, which restrict water flow in the stem.

CROP WATER REQUIREMENTS

In subtropical South Africa, Hoffman and du Plessis (1999) attempted to quantify the water use of six- to seven-year-old trees (cvs. Fuerte and Hass) grown in a deep red clayey soil. They based their assessment on the depth of irrigation water applied (microsprinklers) to rewet the soil back to field capacity (as determined from tensiometers), and on the rainfall falling on the 'wetted' area (assumed to be 70% effective). In the summer, water use peaked at 5 mm d^{-1} for cv. Fuerte and 4 mm d^{-1} for cv. Hass. In the winter, the corresponding values were 1.5–2.0 mm d^{-1} and below 1.5 mm d^{-1}. The annual totals were 1020 and 890 mm, respectively.

In Western Galilee, Israel, on a heavy soil, water uptake occurred at a maximum depth of 1.2 m but with 95% of the water coming from the top 0.60 m. By contrast, in the Northern Coastal Plain of Israel, water uptake occurred at depths down to 1.8 m with a smaller proportion (80%) coming from the 0–0.60 m layer (Shalhevet *et al.*, 1979). Rates of evapotranspiration (ET_c) were relatively constant throughout the irrigation season (June to October) at 3.0–3.5 mm d^{-1}. The ratio ET_c to E_{pan} (USWB Class A) increased over this period from 0.42 (June) to 0.61 (October). The irrigated trees were aged between five- and eleven-years-old, and spaced 6 × 6 m apart.

In Mediterranean-type climates, the mid-summer water application rates recommended for young trees are as follows: year 1, 4–8 L d^{-1} tree^{-1}; year 2, 8–15 L d^{-1} tree^{-1}; year 3, 30–50 L d^{-1} tree^{-1} and year 4, 80–150 L d^{-1} tree^{-1} (Lahav and Whiley, 2002). At a tree density of 278 trees ha^{-1}, the figures for year 4 equate to 2.2–4.2 mm d^{-1}.

In California, growers apply annually between 450 and 1500 mm of irrigation water depending on the location, less in the north more in the south. This is in years with typical rainfall totals between 250 and 500 mm. For mature trees, the recommended crop coefficient $K_c = 0.7$ together with a + 10% leaching factor, dependent on water quality. Local differences in topography and exposure can be important, for example: ET_o values on different sides of a hill varied considerably; in the winter, there was a

120% difference between the bottom, middle and top of a hill, and a 32% difference in the summer (Faber, 2006).

Summary: crop water requirements
1. There have only been a few attempts to measure the actual water use of avocado trees.
2. In Mediterranean-type climates, peak rates of water use (in summer) appear to be between 3 and 5 mm d^{-1}.
3. There are apparent differences in rates of water use between cv. Hass and cv. Fuerte.
4. Water uptake has been recorded at a depth of 1.8 m.
5. For mature trees, the crop coefficient ($K_c = ET_c/ET_o$) is usually within the range 0.4–0.6.
6. There is no published evidence to show that when a tree is flowering its water requirements increase (although this is commonly stated).

WATER PRODUCTIVITY

Sufficient water is needed during the flowering period to ensure adequate fruit set, and during the period of rapid fruit growth to maximise fruit size and to minimise fruit drop. In Mediterranean climates, there is a risk of adverse effects of reduced aeration and soil cooling if excess water is applied during the spring. The need for irrigation is reduced in the autumn and is (usually) unnecessary in the winter (when there is usually enough rain) (Lahav and Kalmar, 1983; Lahav and Whiley, 2002).

Following the experiment in California described above (Richards *et al.*, 1962), one of the early irrigation experiments reported was undertaken in the northern coastal plain in Israel over a six-year period (1968–1974), beginning in the fifth year after planting. The experiment compared four irrigation intervals (7, 14, 21 and 28 day), although this comparison was confounded by differences in the quantities of water applied (mean annual totals 889, 745, 668 and 594 mm, respectively). The soil was a vertisol, with more than 60% clay down to 1.5 m. The aim was to wet the soil profile back to field capacity at each irrigation, to depths of 0.90 m (the 7 and 14 day treatments) and 1.20 m (the 21 and 28 day treatments). Treatments were imposed from early June to the end of October. Vegetative growth (trunk diameter, tree height and volume) was reduced as the irrigation interval increased. The buildup of salts was greatest under the extended interval treatments, although these were leached by winter rain (Kalmar and Lahav, 1977).

Interpreting treatment effects on yields is complicated by the tendency of avocado trees to yield well only in alternate years. The cv. Hass is particularly prone to 'alternate bearing', which in the experiment summarised above was triggered by frequent irrigation. When averaged over all six years, yields of fresh fruit from each of the four irrigation interval treatments were similar for cvs. Ettinger (average *c*. 47 kg tree^{-1}) and Fuerte (40 kg tree^{-1}). But in the case of cv. Hass, there was a 10 kg

tree^{-1} yield advantage in favour of irrigation at weekly intervals compared with every 28 days (63 compared with 53 kg tree^{-1}). Frequent irrigation increased individual fruit weight, particularly with cvs. Ettinger (+ 35 g or 11%) and Hass (+ 18 g or 9%). Irrigation began too late to influence fruit set, but there was a small increase in oil content from frequent irrigation. It was concluded that a 21-day irrigation interval was the most appropriate since it reduced tree size without loss of fruit yield (Lahav and Kamar, 1977).

A similar experiment was conducted by Kurtz *et al.* (1992) over the period 1984–1988 on the coastal plain of Israel. The responses of three cultivars were compared (Ettinger, Fuerte and Hass), all grafted on to Antillean seedling rootstocks, to three levels of water application. These were 70, 100 and 130% of the annual amount recommended in Israel for mature trees (700 mm), after adjusting the value of K_c for tree size (trees were planted in 1980). The soil was a silty loam, evaporation was measured in a USWB Class A pan (April to November total *c.* 1300 mm), and water was applied through one microsprinkler per tree with the rates adjusted so that there was a uniform wetted area of 20 m^2 per tree. For two of the cultivars (the exception being Hass), tree vegetative growth increased with the amount of water applied, such that cv. Ettinger needed additional pruning. For various reasons, fruit yields varied considerably from year to year but when totalled over the five years the only significant effects were the 32% yield advantage of the 130% treatment over the 100% (and 70%) treatments, for cv. Ettinger (47 cf. 35 t ha^{-1}), and a corresponding 15% benefit for cv. Fuerte (40 cf. 32 t ha^{-1}). Over five years, assuming linearity, these represent yield responses to irrigation of 1.1 and 0.7 kg m^{-3}, respectively. Salinity levels in the soil were greatest with the low water applications.

A not very convincing water production function was developed from the results of irrigation experiments conducted on the coastal plane of Israel over a number of years with the same three cultivars (Ettinger, Fuerte and Hass). This suggested that, based on relative yields, a seasonal (summer) water application of 650 mm (in addition to winter rainfall totals of 500–600 mm) was needed to obtain an 'optimum' yield (defined as 0.91 times the maximum). Between seasonal water applications of 300–600 mm, the yield response in absolute terms was 15.7 $\pm$ 3 kg ha^{-1} mm^{-1} (1.57 kg m^{-3}) of fresh fruit (Steinhardt, 1991). Assuming a linear response, this equates to a yield of 10 t ha^{-1} for an application of 650 mm water.

Another experiment in Israel compared four levels of water application (60, 80, 100 and 120% of the 'commonly applied amount' as determined with tensiometers and a neutron probe). Variable nitrogen levels were confounded with the water treatments, which were applied through a drip irrigation system to a clay soil. Tree girths (cvs. Fuerte and Hass) over the seven years of the experiment increased with the annual average depth of irrigation water applied (range 283–572 mm, in addition to winter rainfall). Similarly, yields of fruit increased at 2.2 kg m^{-3} (cv. Hass) and 1.6 kg m^{-3} (cv. Fuerte) (Lahav *et al.*, 1992). The results of this and several other irrigation experiments in Israel were subsequently re-evaluated and confirmed by Lahav and Aycicegi-Lowengart (2006).

The sensitivity of avocado to water deficits was illustrated by the results of an experiment in the Jordan Valley, Israel (32°42′N, 36°35′E; alt. −204 m) in which the responses of avocado trees (cv. Hass) grown in lysimeters to three irrigation frequencies and two soil volumes (100 and 200 L) were described by Silber *et al.* (2011; 2012). Pulsed irrigation, in which water was applied for 10–20 minutes every 30 minutes throughout the day, was compared with a treatment in which water was applied daily from the night to the morning, and a third treatment in which the same quantity of water was applied every alternate day (all through a drip system). Over the three years the experiment lasted, vegetative growth was greatest in the 200 L soil volume at all irrigation frequencies. Differences between irrigation treatments were only statistically significant in the two years when fruit were harvested in the low volume (100 L) soil treatment, when pulsed irrigation outperformed night-time irrigation, which in turn outperformed the alternate day treatment. There were no treatment effects on flowering intensity or fruit set, but fruit drop was greater in the 100 L soil volume treatment than in the 200 L one, and greatest in the alternate day irrigation treatment and least in the pulsed treatment. The authors invoked limitations in carbohydrate supply as being the most likely cause of fruitlet abscission, although no data were presented to support this hypothesis.

The interim results of an irrigation experiment in California were reported by Faber *et al.* (1995). In an area close to the coast with winter rainfall (average *c.* 400 mm), it was not until the fourth year of treatments (consisting of seven different levels of replenishment, from 0.37 to 1.11 ET_o) that there was a difference between treatments in cumulative yields (there was no control 'rainfall only' treatment), reaching nearly 800 kg tree^{-1}. In contrast, tree size in general again increased with the amount of water applied, so that yield per unit of canopy volume declined. At the start of the experiment, the trees (cv. Hass) were six-years-old and had previously been irrigated. The loam soil was deep (> 2 m). A single microsprinkler was used to apply water to each tree at weekly intervals. At this location, in years with adequate rainfall irrigation is only probably needed for a two- to three-month period from mid-July.

The effect of drying the root zone beneath half or all the canopy on water productivity was studied in a field experiment on a sandy soil in Western Australia (31°S, 115°E) by Neuhaus *et al.* (2009). The treatments were imposed for eight months from February (after fruit drop) through to maturity in September (cv. Hass on Guatemalan seedling rootstocks, 15-years-old). In the following season, normal irrigation practices were restored. In both treatments, yields were reduced proportionally more than the reduction in water supply, when compared with the well-watered control treatment, whilst re-watering did not restore yields in the following season. Contrary to expectations, water productivity was therefore reduced. The main impact of a reduced water supply was fruit abscission linked to dry soil around the roots rather than to the water status of the leaves or fruits, which was maintained. There was no apparent adverse effect of drying half the root system on fruit quality. Again, contrary to expectations, there was no evidence to support the concept of 'root signals' influencing leaf conductance and vegetative growth, although there was no explanation for the large fruit drop in the partially irrigated treatment (Neuhaus

et al., 2009). Electrical signalling was however identified by Gil *et al.* (2008) in Chile as a possible mechanism to explain the fast response of stomata of avocado to changes in soil water status, since root to leaf abscisic acid transport alone did not explain the process.

Excess water

The avocado is sensitive to flooding and poor soil aeration, resulting from inadequate or slow drainage, soil compaction, excess rain and/or poor irrigation management leading to high water tables (see Schaffer, 2006 for a detailed review of the topic). This can be a serious problem everywhere. Unlike some other species (e.g. mango), avocado does not possess any anatomical or morphological adaptations in response to low soil oxygen levels. For grafted trees like avocado, flooding sensitivity is primarily due to the rootstock and not to the scion, and attempts are now being made to identify/select for flood tolerant rootstocks, for example in Chile (Fassio, *et al.*, 2011) and in South Africa (Farrow *et al.*, 2011). Root rot (*Phytophthora cinnamoni*) is associated with wet soils, and it was originally thought that damage to avocado trees from wet soil was due to increased destruction of roots by the causal organism. It has since been shown that soil flooding and the resultant hypoxia (reduction in oxygen level) or anoxia (complete lack of oxygen) can damage roots even in the absence of *P. cinnamoni* (Schaffer, 2006). One of the earliest detectable changes is a decline in gas exchange (net CO_2 assimilation and transpiration) as a result of stomatal closure. Visible symptoms include wilting, leaf abscission and root necrosis. The effects of oxygen deficiency on fruit yields have not been well quantified. In flood-prone areas of southern Florida, commercial growers are advised to plant avocado trees on raised beds, 0.9 m high by 0.9–1.5 m wide (Schaffer, 2006). Research needs to be focused on how the root systems respond to waterlogging.

Salinity

Among fruit trees, avocado is the most salinity-sensitive crop, but the races differ in their relative sensitivity. Rootstocks and seedlings of Mexican race cultivars are considered to be the most sensitive to saline conditions, and those of the Antillean race the most tolerant. Chloride toxicity is the major contributing factor, aggravated by sodium. The advice given to growers in Israel is that the chloride content of water used to irrigate avocado should not exceed 120–150 mg L^{-1} for Mexican rootstocks and 200–250 mg L^{-1} for Antillean rootstocks (Schaffer and Whiley, 2002; Wolstenholme, 2002). Examples of some of the research on salinity are presented below.

Several long-term experiments have been carried out to quantify the yield responses to salinity of avocado and to specify critical levels that should not be exceeded. For example, Lahav *et al.* (1992) reported the preliminary results of a salinity experiment in Israel in which the responses of two rootstocks to four levels of salinity (chloride) in the irrigation water were compared. There were two levels of irrigation, 85 and 115% of the recommended amount (applied with microjets). The chloride concentrations in the leaves were three times higher in the trees grafted (cvs. Ettinger and Hass) on

Mexican rootstocks than in those on Antillean rootstocks. Increases in the chloride content of the water from 90 to 380 mg L^{-1} reduced the cross-sectional area of the trunk. Tree growth was faster at all levels of salinity in the treatment where excess water was applied. Fruit yields over the four to five years of records responded in a similar way, declining by 25% on average over the same range of salinity levels.

Later, Shalhevet (1999) summarised the complete set of results from the same experiment for the period 1984 to 1994 (although the stated chloride levels cited were slightly different, namely 80 to 400 mg L^{-1}). The mean salinity level of the soil solution was about 1.8 times that of the irrigation water, and increasing the quantity of water applied did not result in substantial leaching during the irrigation season. Rather, winter rainfall leached the accumulated salts. As expected, trees grafted on Mexican rootstocks showed greater sensitivity to salinity than those on Antillean rootstocks. For those on Mexican rootstocks, average yields (for both scions) declined from about 40 to 15 kg tree^{-1} over the range of chloride levels tested (the trees were five- to eight-years-old).

A second example of salinity research is the long-term (six years) experiment in California described by Oster *et al.* (2007) in which the effects on fruit yield (cv. Hass on Mexican seedling rootstock) of the amount of saline irrigation water applied (0.9, 1.1 and 1.3 ET_c were targeted) and the frequency of application (one, two or seven times a week) were assessed. In the introduction to their paper, the researchers also succinctly summarised previous research on this topic. The average electrical conductivity and chloride concentration of the water, corrected for rainfall, were 0.7 dS m^{-1} and 1.8 mmol L^{-1}, respectively. Trees irrigated seven times a week yielded less than those irrigated less frequently. During the last two years of the experiment, when yields no longer increased with the age of the tree, yields of the two less frequently irrigated treatments both increased with the amount of water applied. This was because the soil water salinity level had not reached a critical level of about 4 dS m^{-1}, when water uptake by the roots is restricted. The critical or threshold electrical conductivity value, beyond which yields declined due to toxicity, was estimated to be 0.57 dS m^{-1} (a very low value compared with other crops). The rate of decline in relative yield was then linear, with a slope of −0.63 per unit of salinity. The authors concluded that, for this cultivar and rootstock, the average annual salinity of the irrigation water, after allowing for the dilution effect of rain, should not exceed 0.6 dS m^{-1} for maximum yields.

As growers rely increasingly on saline water for irrigation so does the need to identify cultivars with improved salinity tolerance, which can be incorporated into a breeding programme (Crowley, 2004). In California, several rootstocks, some of which were selected in Israel, have been shown to have a greater capacity to exclude chloride and sodium. The relative sensitivity of root growth to salinity compared with shoot growth was demonstrated in an experiment in which avocado seedlings were grown in nutrient solution. As a result, Bernstein *et al.* (2004) recommended that root growth should be considered as an important criterion for judging the tolerance of rootstocks to salinity.

Summary: water productivity
1. There is very little reliable evidence on the water productivity of avocado.
2. This is due in part to the difficulty of undertaking long-term irrigation experiments on a tree crop that bears fruit in alternate years.
3. Although quantitative data are lacking, it is commonly stated that 'sufficient water' is required during flowering to ensure 'adequate' fruit set, and during the period of rapid fruit growth to 'maximise' fruit size and to minimise fruit drop.
4. Examples of yield improvements are limited as there is rarely an unirrigated 'control' treatment for comparison, or insufficient information is given in the paper to enable water productivity to be calculated.
5. The best estimate of water productivity (based on relatively low yields, *c.* 9–10 t ha^{-1}) is between 1 and 2 kg fruit m^{-3}.
6. Although the cultivars responded differently, an early recommendation in Israel was to irrigate every 21 days, since tree size was reduced without loss of fruit yield.
7. Soil flooding and the resultant reduction in oxygen level can damage roots even in the absence of root rot. The effects on fruit yields have yet to be quantified.
8. Avocado is particularly sensitive to salinity, notably chloride ions. Rootstocks vary in their sensitivity. The Mexican race is the least tolerant and the Antillean the most.

IRRIGATION SYSTEMS

Drip irrigation of avocado trees began on hillsides in San Diego County, California, during the 1970s. Hillsides offered natural protection from frosts, the land was cheaper than elsewhere, and there was less risk of urban encroachment. Other factors that favoured drip irrigation included the high cost of water, salinity and opportunities to automate the system (Gustafson, 1979).

In California, young trees are irrigated with one dripper or a modified microsprinkler (with a cap that can be removed later as the trees grow). Most growers convert to microsprinklers, or remove the cap, in the second or third year after planting to wet a larger area. Only a few older orchards still use high pressure, solid set sprinkler systems (Faber, 2006).

At Malaga in the south of Spain, Olalla *et al.* (1992) compared drip irrigation at four levels of application (three drippers per tree, with $K_c = 0.44, 0.57, 0.66$ and five drippers per tree, $K_c = 0.57$) with microsprinklers at two frequencies (two and three day irrigation intervals, $K_c = 0.50$ and 0.46). Evaporation was estimated from a USWB Class A pan. The average annual depth of water applied, through a fully automated system, to each treatment over the three years the experiment ran, ranged between 674 mm (drip, $K_c = 0.44$) and 1024 mm (five drippers, $K_c = 0.57$). Because of direct evaporation losses from wet soil, the larger the proportion of wetted soil surface the greater the water application necessary, particularly with microsprinklers. Although there were differences in vegetative growth, fruit yields were similar (cv. Hass, five- to seven-years-old). In an unconvincing report, the principal conclusion was that, when

estimating how much water to apply to a coarse textured soil, K_c should be no less than 0.55.

Flood irrigation should be avoided where there is a risk of hypoxia or anoxia (Lahav and Whiley, 2002). Irrigation is used for frost protection in susceptible areas such as Florida, either by means of microsprinklers (to release heat from the soil by conductance to protect the lower limbs of the tree) or over-tree sprinklers (release of latent heat as the water freezes).

Irrigation scheduling

In a review of the literature on irrigation scheduling, du Plessis (1991) strongly recommended the use of tensiometers in commercial avocado orchards. The critical matric potentials, below which the soil should not be allowed to dry, at depths of 0.30 m were −30 kPa for sandy soils and −50 kPa on clayey soils. The review emphasised that water deficits during flowering, fruit set and early fruit growth should be avoided and that over-irrigation should be avoided at all cost, because of the risk of soil oxygen deficiency and root rot. Tensiometers (installed in pairs at depths of 0.30 and 0.60 m) are also recommended in California (Anonymous, 2011), in order to refine the decision about when to start irrigating and to check that excess water is not being applied. Careful and representative siting of these instruments is essential if reliable data are to be collected. However, as Faber (2006) noted that 'there are quite a few growers who do go out and read their tensiometers on a regular basis and schedule irrigations based on those readings. There are also a lot of rusted tensiometers out in the fields where growers gave up using them'.

Plant-based scheduling methods have also been proposed. For example, Turner *et al.* (2001) compared the use of stomatal conductance measurements to schedule irrigation (at 25% of full conductance, an arbitrary number) with the water balance method based on a Class A pan (water applied $= 1.2\ E_{pan}$, which kept the stomata open except during hot weather). Over a season, scheduling by stomatal conductance reduced the water applied by one third; it also reduced leaf gas exchange and the number of fruits on the trees relative to the water balance method. Because of its complexity, stomatal conductance measurement was not a recommended scheduling method for commercial use. In Israel, Winer and Zachs (2007) have proposed a plant-based method of scheduling for avocado based on daily measurements of changes in the diameter of the trunk.

In order to improve water productivity and to minimise pollution, Kiggundu *et al.* (2012) evaluated several combined irrigation scheduling and nutrient management practices in southern Florida (25°20′N, 80°20′W; alt. 4 m). The amount of leaching, and the productivity and nutrient status of young avocados (cv. Simmonds; irrigated with microsprinklers from planting) were monitored in a four-year study. Basing the irrigation timing on the soil water status reduced the volume of water applied by 87%, and the quantity of phosphorus leached by 74%, compared with irrigating to a set schedule (twice a week for two hours, this being local practice). Tensiometers, installed at depths of 0.15 and 0.20 m, were programmed to switch on the irrigation when

the soil–water potential reached -0.15 kPa. The water saving was even better when irrigation was scheduled using the conventional soil–water balance approach (when $ET = K_c \times ET_o$). Fruit yields were however below those obtained from the soil–water-based treatments with the corresponding fertiliser inputs. Water productivities ranged from less than one kg fresh fruit per m^3 of water applied (set schedule) up to 12 kg m^{-3} (water balance): the overall average irrigation water productivity was about 7 kg m^{-3}. These figures are considerably greater than those quoted above. Experiments of the type described here are notoriously difficult to do well as it is impossible to avoid confounding more than one variable in order to compare like with like.

Water conservation

Some water management issues that have emerged as politically important include the following:

The avocado industry in Australia is committed to improving water productivity, with a vision of doubling irrigation efficiency (however, that is defined) by 2020. This is despite the fact that the industry is a relatively small consumer of water on a national scale ($<1\%$). Irrigation water use varies considerably across the principal areas where avocados are grown, from 300–500 mm in the high rainfall areas in northern Queensland to 800–1800 mm in areas further south and in parts of Western Australia (Anonymous, 2006). In this context, Aleemullah *et al.* (2001) studied irrigation practices on four avocado farms over two years (2000 and 2001) in Queensland. Using capacitance probes to monitor water use, and recording how much water was applied and when, they attempted to establish benchmarks by which to judge good irrigation practice. Irrigation water productivities varied from a low of 50 trays of fruit per million litres to a high of 532 trays per million litres. Assuming each Australian tray contains 6 kg of fruit, these equate to 0.3 and 3.2 kg m^{-3}, respectively, a ten-fold difference. This gives an idea of what it is possible to achieve in practice.

Similarly, new water quality regulations are being imposed in California. No contaminants in water are allowed to leave a grower's land (this often occurs with winter rainfall), including sediments. Growers are expected to monitor water quality themselves (Faber, 2006).

Increasingly, producers will be judged, by governments, supermarkets and consumers, on water management criteria such as these.

For areas where there are restrictions on the availability of water for irrigation, a number of water conservation strategies have been identified by Witney and Bender (1992). Although these strategies were intended for growers in California facing mandatory reductions in water availability, some have general application and include the following:

- Use a science-based irrigation scheduling method (such as tensiometers or capacitance probes).
- Do not irrigate diseased or damaged trees.

- Cut back/stump trees that have attained 100% canopy cover to a height of 1.2–1.8 m, whitewash immediately to prevent sunburn, and allow the trees to re-grow. Stump in alternate one hectare blocks; irrigation frequency can then be reduced.
- Thin-crowded orchards by removing alternate trees before they have achieved full canopy cover, but when the trees have already grown into each other. Sprinklers next to thinned trees can be capped.
- Mulch young trees: keep them weed free.

Mulching

The benefits that can be obtained from mulching go beyond water conservation. These were demonstrated by Wolstenholme *et al.* (1998) in South Africa. In an experiment lasting three years, the application of 150 mm depth of composted pine bark to six-year-old trees (cv. Hass on Duke 7 rootstocks) increased the average annual yields over the following three years by 23% (from 20.0 to 24.4 t ha^{-1}). This period included two good cropping years either side of one 'off' year. The yield benefit followed an average 7% increase in fruit size (and more export-quality fruit) and a 15% increase in fruit number. This response was not just due to water conservation, since the trees were irrigated (drip). Feeder roots proliferated in the pine bark mulch, which supplemented a natural mulch of leaf litter. Stress levels were reduced (e.g. leaf temperatures were up to 6 °C cooler), there was less pedicel ring-neck, and seed coat degeneration was delayed. With a half-life of five years, the commercial application of this mulch, although expensive, was considered to be financially viable, and it was recommended that mulching should become a standard crop management practice. Careful choice of the mulching material is necessary, and Whiley (2002) has listed some of the materials used in Australia. These include barley and sorghum straw, sugar cane tops and groundnut husks. Fire and frost are possible hazards associated with mulching.

Summary: irrigation systems
1. Both drip and under-tree microsprinklers have been/are successfully used to irrigate avocado trees.
2. Basin irrigation is not recommended.
3. The proportion of the root zone that it is necessary to keep wet has not been clearly established.
4. The value of the crop coefficient depends on the method of irrigation and the frequency and degree of wetting the soil surface but, for mature trees, a value of about 0.6 is reasonable.
5. Tensiometers (and capacitance probes) are recommended for scheduling purposes: the soil should not be allowed to dry, at depths of 0.30 m, below soil matric potentials of -30 kPa on sandy soils, and -50 kPa on clayey soils.
6. Plant-based indicators of when to irrigate may be worth considering.
7. Mulching of young trees is a recommended water conservation measure and has other benefits.

8. External pressures to encourage growers to use water effectively and wisely will increase.

CONCLUSIONS

Although, globally, avocado production is dominated by Mexico and other tropical countries, most of the research summarised here has been done in subtropical regions, notably Australia, California, Israel and South Africa. Unfortunately, much of the research reviewed in this paper was poorly reported, and the data sometimes difficult to interpret. Of 60 references cited on avocados, only a quarter were in refereed journals, whilst a half had been published in 'the grey literature' as proceedings of conferences or yearbooks, sometimes with limited quality control. The remainder were chapters in books, and in one excellent book in particular (Whiley *et al.*, 2002), and extension leaflets. In part, the emphasis on conference proceedings is understandable, given the active support given to research by grower associations in a number of countries and the need for stakeholders to be kept informed. The long-term nature of irrigation research on tree crops in particular, and its cost, makes it imperative that the (often incomplete) results of research are communicated regularly to the industry. Sometimes, this is at the expense of publishing in peer-reviewed papers the science on which recommendations to growers are based. Getting the balance right is not easy.

Despite avocado's importance as an irrigated crop, and the diverse environments in which it is grown, there have only been a few attempts to measure its actual water use, and to quantify water productivity in systematic ways. Much of the research is empirical and lacks generic application. There has been only a limited amount of fundamental research on the water relations of avocado to assist in the extrapolation of results from one location to another. As growers rely increasingly on saline water for irrigation so there is an increasing need to continue to identify cultivars with improved salinity tolerance. There is great variability in responses to water (and salinity) due to year-to-year variability, site-to-site differences, rootstock and scion interactions, and cultural practices, such as plant population. This makes research on avocados particularly challenging.

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