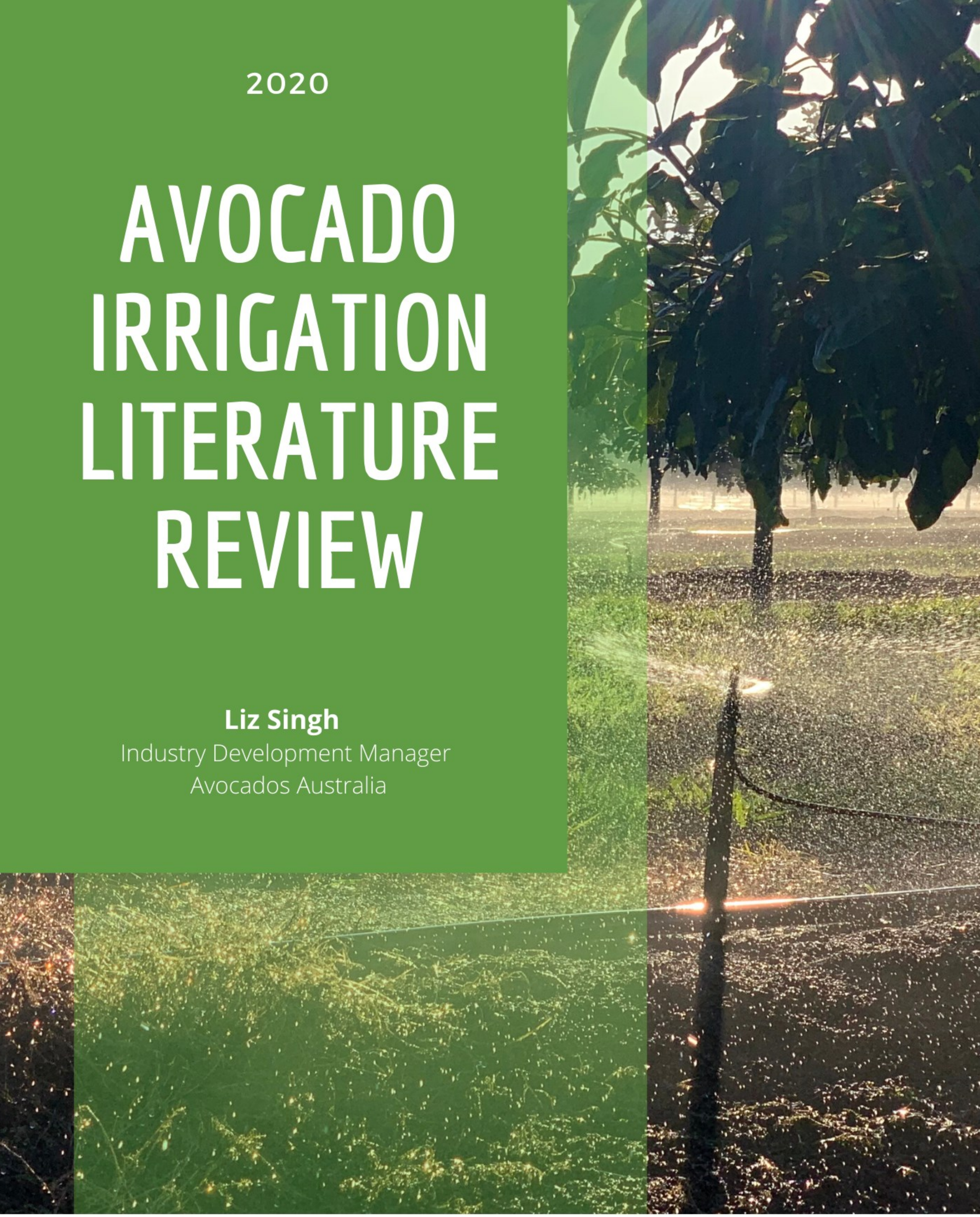

2020

AVOCADO IRRIGATION LITERATURE REVIEW

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2. Acknowledgements

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4. About the project

The ***Avocado Industry Development and Extension*** project (AV17005) is tasked at improving Australian avocado orchard productivity, fruit quality and profitability through the promotion of best practice. This project connects growers with current and relevant information to support the informed decisions required to produce quality avocado fruit for consumers. The project is co-delivered by the Department of Agriculture and Fisheries (DAF) and Avocados Australia (AAL) with collaboration from the Western Australian Department of Primary Industries and Regional Development (DPIRD).

Since commencing in 2019, the project team has travelled to all Australian avocado growing regions, delivering grower selected topics at the Avocado Regional Forums. The project didn't stop when COVID – 19 arrived but went on-line before launching the Avogrow webinar series.

Capital city wholesaler meetings also kept agents and wholesalers up-to-date with recommended fruit handling procedures and relevant industry developments.

The project team received an outstanding response to the AvoSkills workshops held in North Queensland and Western Australia, with workshop capacity not large enough to accommodate everyone who wanted to attend the best practice intensive workshops. If you missed out, keep an eye out for future events.

Understanding grower needs is a top requirement for the project. Grower suggestions have led to the release of the project's first video reviewing Phytophthora control in the orchard. Growers have also been receiving monthly reminders for orchard action through the AvoAlerts.

The project team travelled with growers to California in September 2019 and on to the IX World Avocado Congress in Colombia. Information about these trips, regional forums, Avogrow webinars and general best practice information can be found on in the Best Practice Resource (BPR) located on the Avocado Australia website (www.avocado.org.au/bpr/) and maintained by this project as an information resource for all growers and industry members participating in the Australian Avocado Industry.

Growers are encouraged to get in touch with the project team, your feedback makes this project better.

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5. Irrigation Introduction

Avocado trees are evergreen, have strong vegetative growth periods and large transpiring canopies. They have a reported photosynthetic capacity to produce more than 30t/ha of fruit (Wolstenholme 1986), yet the Australian national average is 9.23t/ha (Hall 2015).

Is water management the missing link?

Water is essential for avocado production. Water supplied through irrigation provides the opportunity for growers to influence the growth and development of an avocado crop. Yet avocados are sensitive to excess or deficit water availability. Developing irrigation practices that meet tree water requirements is critical for tree growth and development, orchard health, yield, fruit quality and profit margins.

While irrigation best practice information for the Australian avocado industry has been detailed in the Best Practice Resource on the Avocados Australia website (www.avocado.org.au), avocados are grown in different climatic conditions and soil types around Australia making it difficult to develop a one size fits all approach.

Additionally, climatic conditions are becoming hotter, dryer and water quality and availability is no longer a secure assurance. Regions that traditionally grew rainfed orchards are now installing irrigation to supply supplementary irrigation. Applying water when it is available in dry times is now widely practiced as well as orchards that rely solely on irrigation to make avocado production a surety in dry hot environments e.g. Tristate.

Growers interested in improving their irrigation practices (efficiency and effectiveness) must look at their soil type, variety, rootstock, the infrastructure they have on farm, the age of the irrigation system, the filter system, water quality, automation and maintenance as well as the volume of water applied, when to apply it, where the water should be distributed and how to monitor it.

Understanding the impact of the above factors can help develop and maintain an orchard that produces successful yields and fruit quality annually but the role of tree water relations specifically physiological (e.g. transpiration) and phenological (e.g. flowering) are essential to taking the next step in irrigation best practice.

This review has developed a summary of information that relates to physiology and phenological cycles as background to making decisions about applying water through irrigation. It is combined with a review of approximately the last decade looking at irrigation research in avocados targeting specifically the impacts of water availability, irrigation practice, water productivity and monitoring.

The review is divided into sub-titles to allow for quick selection of relevant information.

Please note a lot of the information presented in this review was not conducted in Australia and therefore the timing of phenological stages may not occur in the same months as Australian orchards.

For further information about the physiology and phenology of the avocados in relation to water, a valuable resource is Carr 2013 – The water relations and irrigation requirements of avocado (*Persea americana* Mill.): A review.

6. Tree Water Relations

Transpiration is the process by which avocado trees absorb water from the soil through their roots, transport it through the trunk /stems (xylem) as sap to the leaves where it evaporates from stomatal pores on the underside of the leaf, back into the environment (Figure 1).

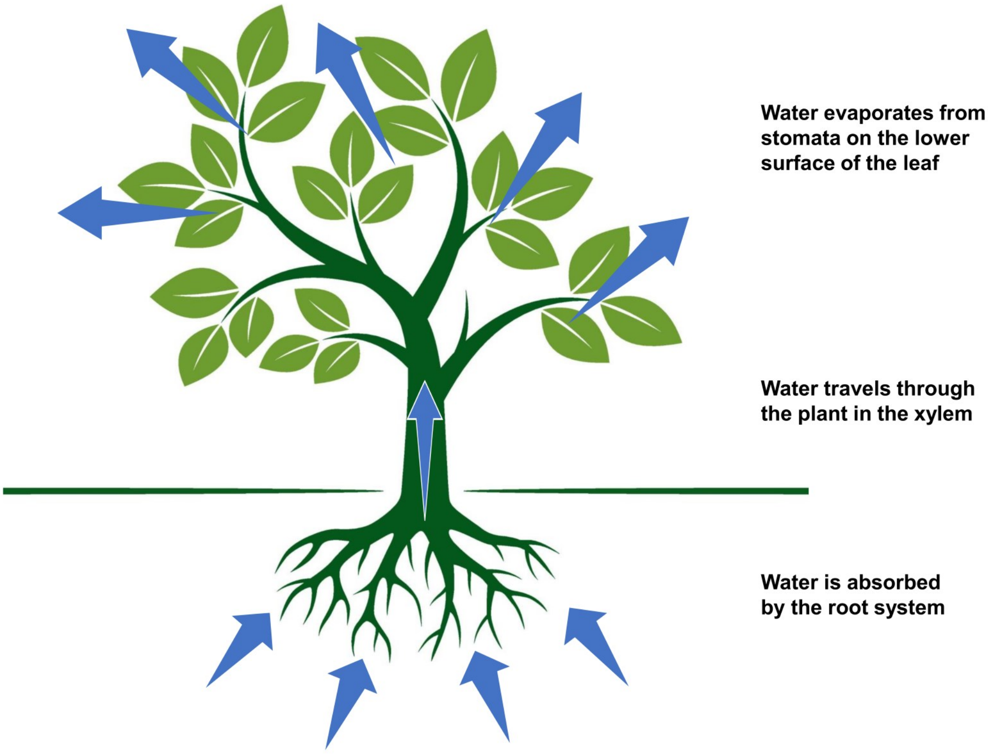


Figure 1 – Process of Transpiration (Singh & Singh 2018).

Tree water relations primarily describe how the tree reacts (physiology) to changes in water availability and surrounding environmental conditions or changes in growth cycle water requirements (phenology). These reactions influence transpiration (speed and volume) and predict the impacts on fruit yield and quality when water delivery does not meet tree water requirements (time or volume).

Water availability is well known to affect yield and fruit quality but what is not obvious is how. Environmental constraints, irrigation management strategies or systems lacking capacity all contribute to final yield and fruit quality.

Figure 2 broadly demonstrates the flow-on effects water availability can have on basic tree physiology and phenology. Closure of stomates results in reduced photosynthetic rates and the energy (assimilates / carbohydrates) required for crop growth and development. Equally water availability influences soil nutrient availability and uptake and the production of important amino acids required for growth and development. The domino effect that water availability has on tree physiology is also relevant to phenology as roots, leaves, flowers and fruits compete for the water and energy resources necessary to maximise yield and quality.

Too little or too much water has consequences, but knowledge of these impacts can assist in developing informed irrigation decisions.

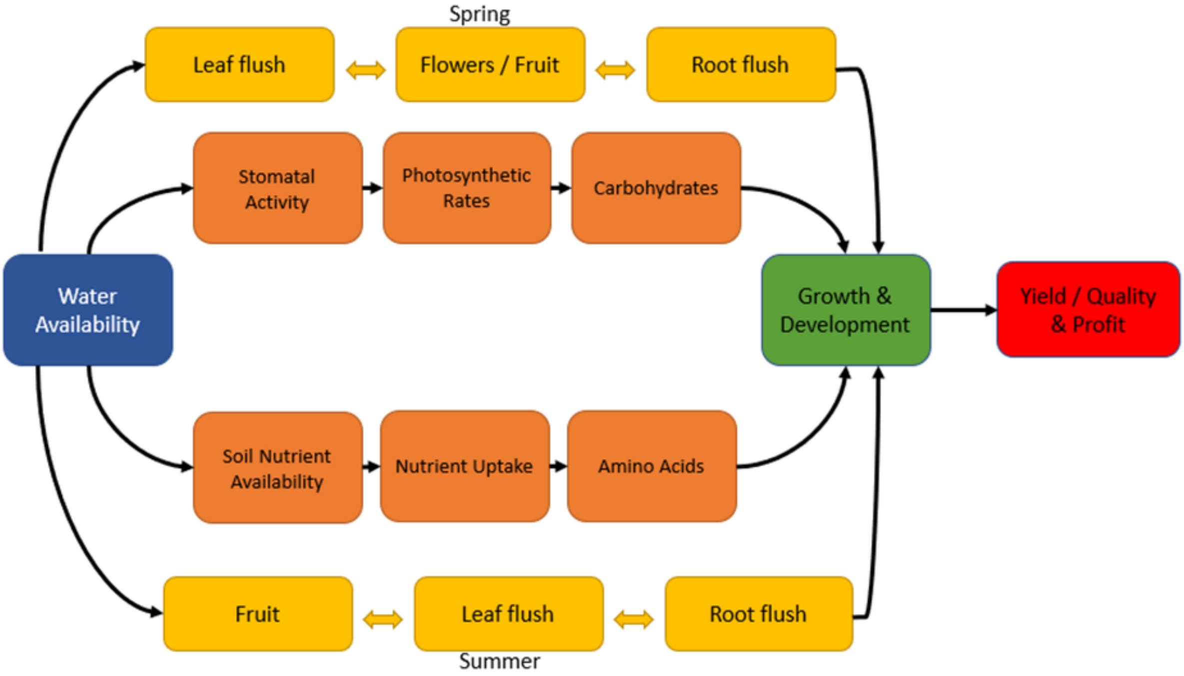


Figure 2 – Water availability impacts on avocado physiological processes (orange boxes) and phenological growth stages in spring and summer (yellow boxes). (Singh & Singh 2020).

6.1 Water deficit

Low water availability causes avocado canopy growth and development to decrease as water becomes less available in the root zone. A less active canopy (reduced leaf area, shoot length, total canopy volume) has future consequences for cropping (Silber *et al.* 2013) as photosynthetic capacity and carbohydrate production is compromised.

Decreases in sap flow were recorded over a 44 day soil drying period by Neuhaus *et al.* 2007 (Figure 3). Tree function is considerably less in the dry (DD) treatment in comparison to the well-watered (WW) optimal treatment. Following a change in treatments at day 45, it took the dry (DD) treatment only 7 days to return to the leaf water potential of the well-watered treatment though sap flow measurements continued to operate in a low range.

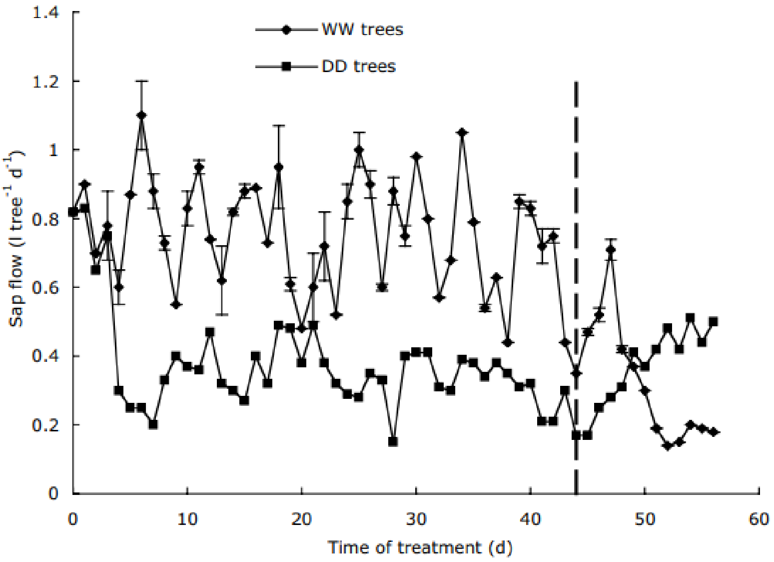


Figure 3 – Trunk sap flow in avocado trees subjected to split root drying treatments, DD – dry on both sides, WW – well watered on both sides (Neuhaus *et al.* 2007).

Neuhaus *et al.* 2007 observed the impacts of soil drying on physiological function and physical implications as illustrated in Figure 4.

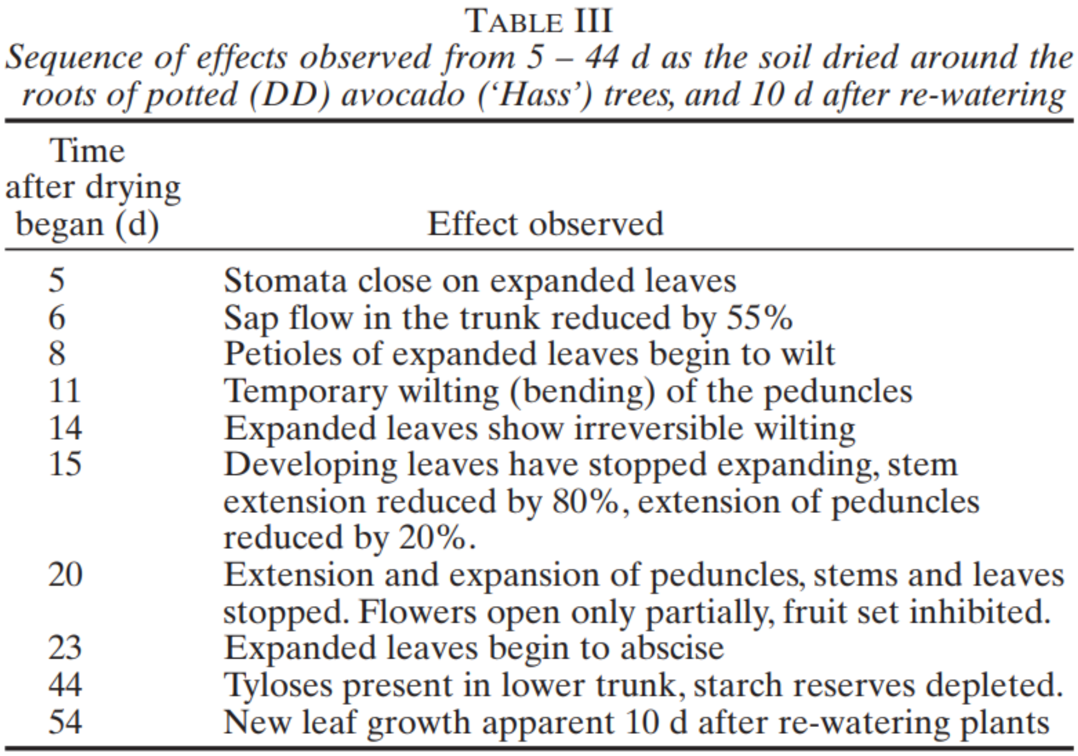


TABLE III

Sequence of effects observed from 5 – 44 d as the soil dried around the roots of potted (DD) avocado ('Hass') trees, and 10 d after re-watering

Time after drying began (d)	Effect observed
5	Stomata close on expanded leaves
6	Sap flow in the trunk reduced by 55%
8	Petioles of expanded leaves begin to wilt
11	Temporary wilting (bending) of the peduncles
14	Expanded leaves show irreversible wilting
15	Developing leaves have stopped expanding, stem extension reduced by 80%, extension of peduncles reduced by 20%.
20	Extension and expansion of peduncles, stems and leaves stopped. Flowers open only partially, fruit set inhibited.
23	Expanded leaves begin to abscise
44	Tyloses present in lower trunk, starch reserves depleted.
54	New leaf growth apparent 10 d after re-watering plants

Figure 4 – Observed impacts of total root drying over 44 days and 10 days after re-watering (Neuhaus *et al.* 2007).

Cutting irrigation to contend with lower water availability could result in significant changes to production. Silber *et al.* 2019 demonstrated that water deficit during early season growth resulted in leaf chlorosis, increasing in severity as flower buds emerged and flowering occurred. The consequence was significant leaf defoliation and fruit abscission. Fruit abscission increases significantly with water stress as insufficient carbohydrates are available to support developing fruit (Silber *et al.* 2019, Neuhaus *et al.* 2007).

Elongation of vegetative growth (trunks, branches, leaves, peduncles) will be restricted with low water availability though reproductive tissues (e.g. flowers) don't seem to be adversely affected (Neuhaus *et al*. 2007) or maybe are considered more important when supporting growth under low water availability.

Neuhaus *et al.* 2009 showed that leaf conductance still remained as high in partially dried treatments as the well-watered treatment. Total drying of the soil profile negatively affected leaf conductance, yet it recovered quickly following re-watering similar to the previous study described above (Figure 5).

Moreno – Ortega *et al.* 2019 determined constant water stress (40-60% of the FAO-56 calculated crop evapotranspiration tree water requirements) throughout the growing season reduced yield by 30% and increased drought stress under high evaporative demand but showed no effects on the physiological parameters of photosynthesis, chlorophyll content or leaf mass area suggesting that a standard reduction of water across the season could be achievable in times of drought.

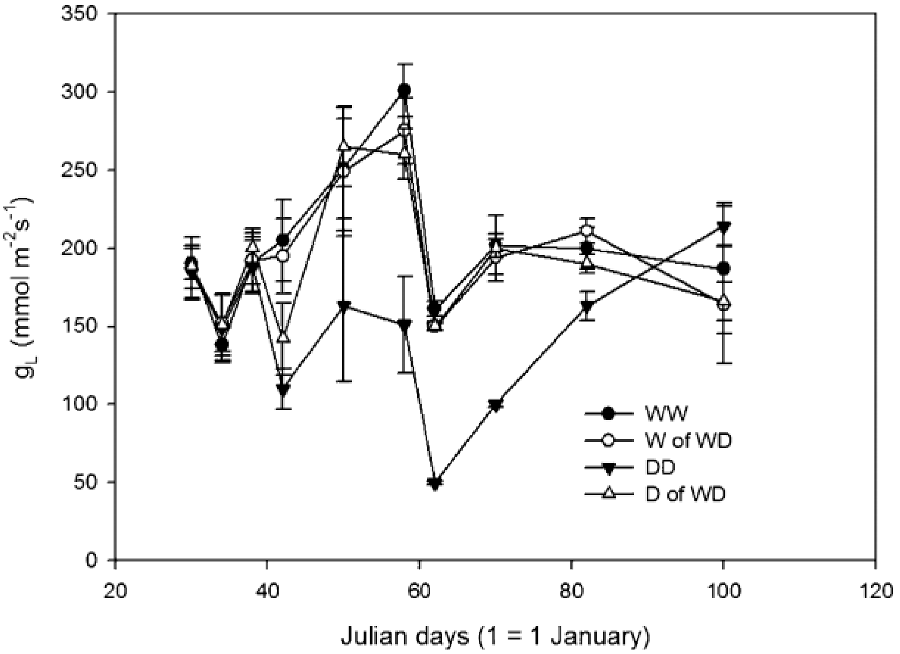


Figure 5 – Leaf conductance (g_L) measured at midday in avocados trees subjected to split root dying treatments – WW (well-watered both sides), W of WD (measured in the watered side of a wet / dry treatment), DD (drying on both sides), D of WD (measured in the dry side of a wet / dry treatment (Neuhaus *et al.* 2009).

Neuhaus *et al.* 2007 demonstrated that total drying of the soil profile caused tyloses (Figure 6) to form, blocking xylem vessels of water stressed trees but not in partially watered or well-watered trees. In the dry treatment 33% of xylem vessels were blocked by tyloses, preventing further stress by reducing the amount of water that is required to maintain water pressure and conductance in the trunk. Tylose development may assist the tree survival under severe rootzone drying but the blockage of the xylem vessels could be permanent and reduce long-term tree function and productivity.

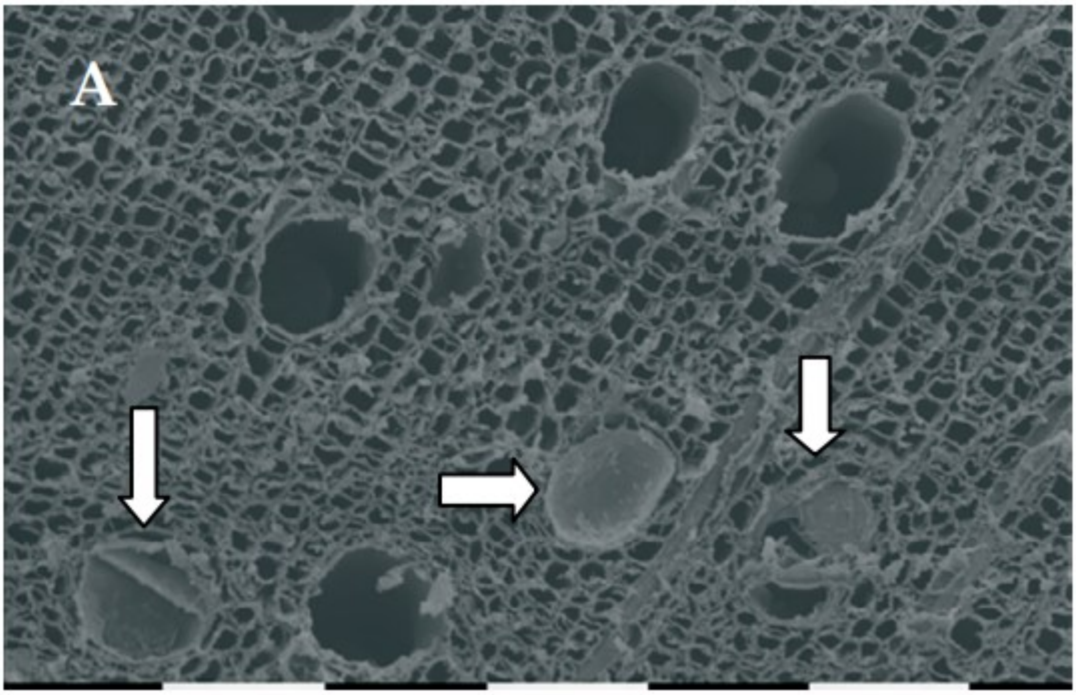


Figure 6 – Tylose growths blocking xylem vessels in avocados subjected to severe rootzone drying. Bars = 100 µm (Neuhaus *et al.* 2007).

Tyloses are not the only concern for avocado trees suffering dry times. Neuhaus *et al.* 2007 also demonstrated that tree carbohydrate reserves are depleted in dry condition trees. Figure 7 shows the pink carbohydrate reserves of the well watered treatment (A) and the wet / dry treatment (B), while the carbohydrate reserves of the dry / dry treatment is significantly diminished (C). With the reduction in photosynthetic capacity, the tree must rely on carbohydrate reserves to provide the energy required for tree survival and a considerable period of time is required for these carbohydrate reserves to be built back up after watering has recommenced; 56 days after re-watering (D) and 84 days after re-watering (E).

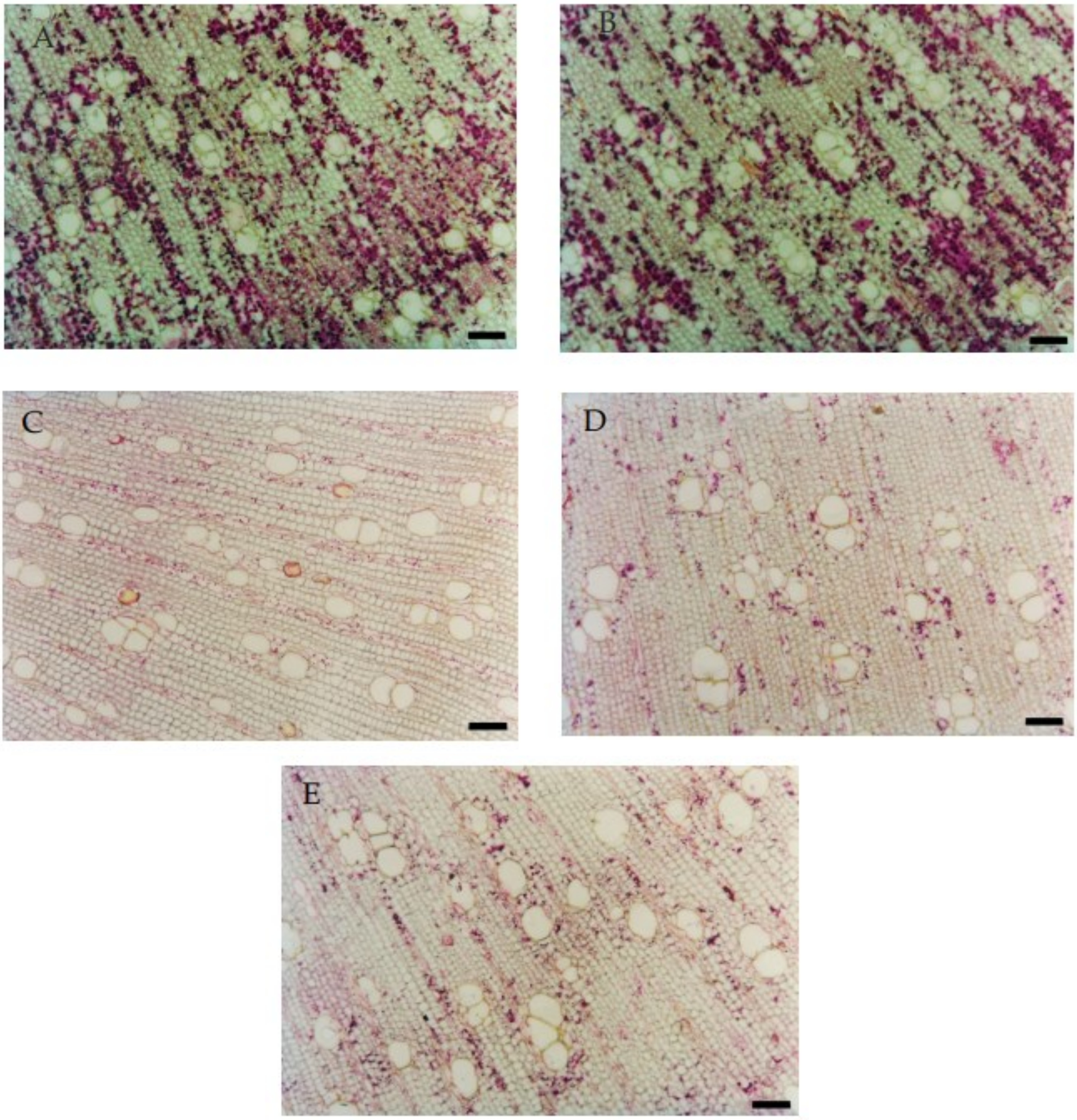


Figure 7 - Carbohydrate content of well water versus dry condition trees (Neuhaus *et al.* 2007).

Cross sections of the trunk bases. The red colour indicates starch abundance in xylem parenchyma and ray cells of well watered trees (A) and wet / dry treatment and is almost absent in the dry / dry treatment (C). Starch begins to accumulate again after the dry / dry treatment is re-watered; (D) 56 days after re-watering, (E) 84 days after re-watering. Bars = 100 µm.

6.2 Overwatering / Flooding / Hypoxia

In soils that have high bulk densities, are compacted and poor draining; flooding or water logging can occur due to irrigation design, management or climatic conditions leading to root rot and production issues. Avocado roots have a high oxygen requirement (>17-30% - Ferreyra *et al.* 2007) and do not favour water logging.

Low oxygen in avocado soils is not only caused by the soil's physical characteristics and bulk density but also the soil water-to-air ratio that changes with each irrigation event. In an extensive study conducted by Gil *et al.* 2008a, it was shown that high soil water content displaced the soil oxygen resulting in a high soil water-to-air ratio and this had substantial impacts on the rate of oxygen diffusion in the soil (Figure 8). It lowered the final dry weight of avocado tissues (total, wood, leaves, roots), reduced the number of leaves and flowers present, the net CO_2 assimilation declined and the vascular anatomy of root and shoot tissue changed (Figure 9).

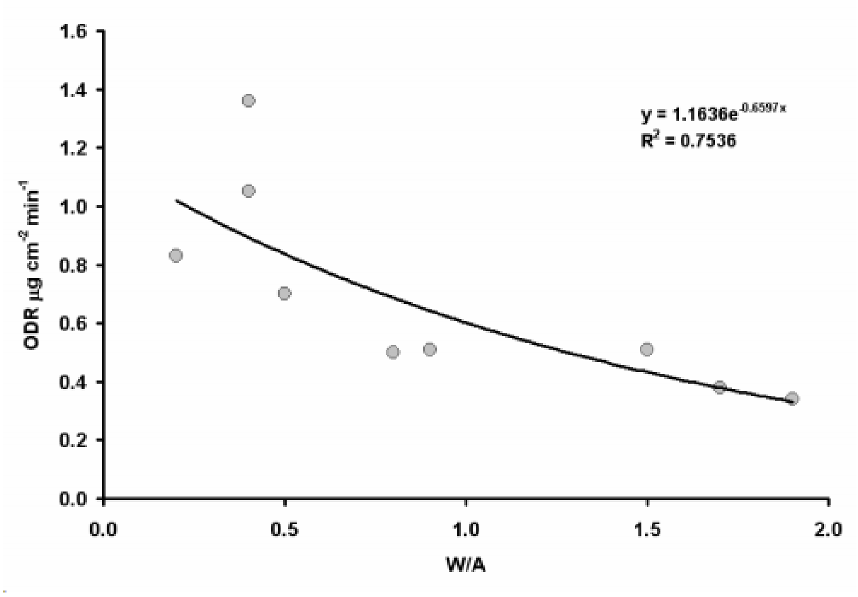
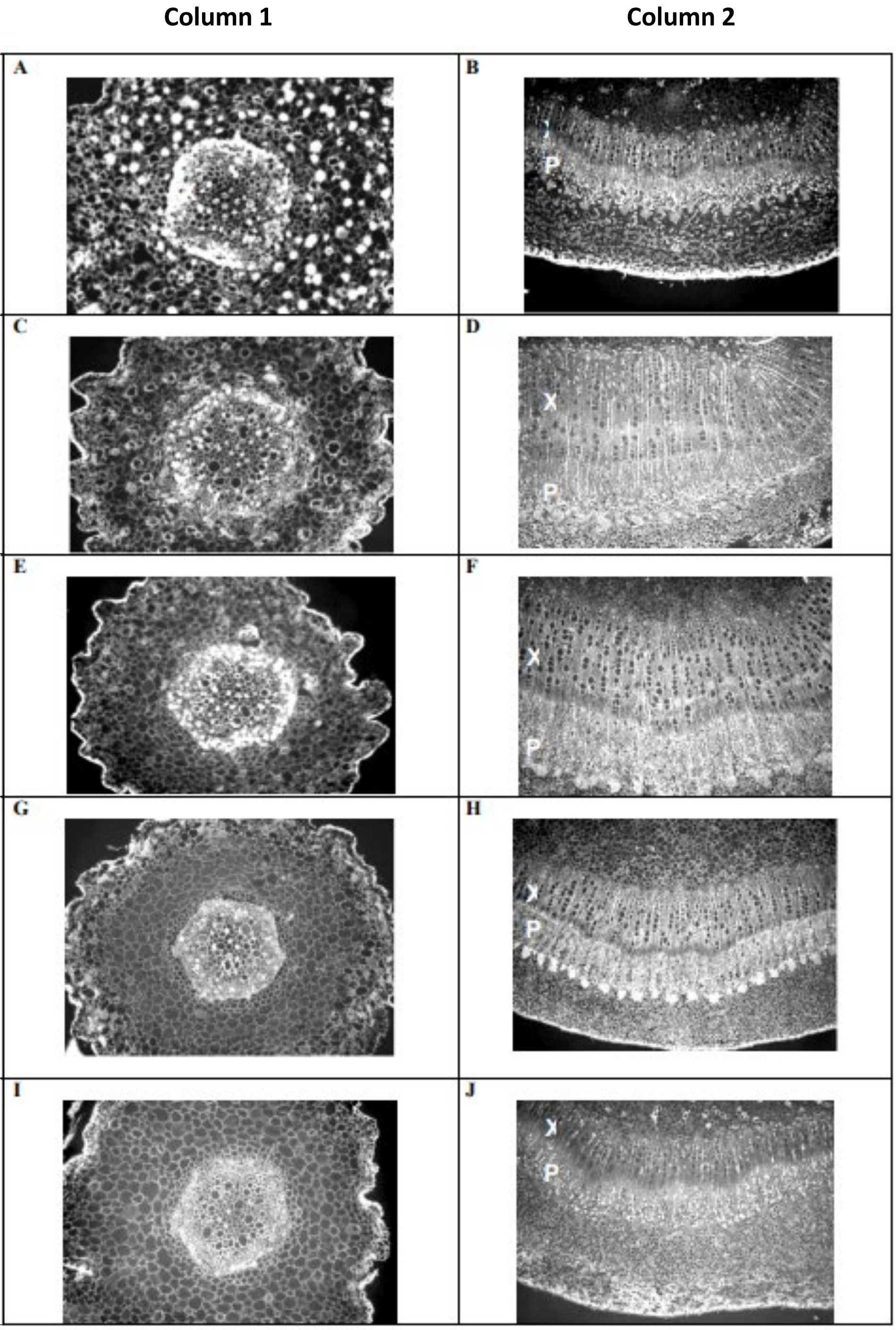


Figure 8 – Relationship between the soil water-to-air ratio (W/A) and soil oxygen diffusion rate (ODR) (Gill *et al.* 2008a).



Treatment 1 - trees in fine loam clay soil irrigated frequently with water content near field capacity, average W/A=1.7 and an average seasonal soil air content of 17.4%.

Treatment 2 - trees in loam clay soil irrigated frequently with water content near field capacity, average W/A=1.3 and an average seasonal soil air content of 19.5%.

Treatment 3 - trees in 21 loam clay soil with higher silt content, irrigated frequently with water content near field capacity, average W/A=0.6 and an average seasonal soil air content of 35.0%.

Treatment 4 - trees in loam sandy soil irrigated frequently with water content near field capacity, average W/A=0.4 and an average seasonal soil air content of 32.8%.

Treatment 5 - trees in sandy soil irrigated frequently with water content near field capacity, average W/A=0.3 and an average seasonal soil air content of 36.8%.

Figure 9 – Vascular anatomy of avocado root *(column 1)* and Spring shoot tissues *(column 2)* with different soil water-to-air ratios (Gil *et al*. 2008a). X = xylem, P= Phloem .

Figures 10 - Two-year-old 'Hass' on Mexicola rootstock growing at 29% (left) and 7% (right) soil air content (Ferreyra *et al.* 2010).

Roots need oxygen for the process of respiration which allows the carbohydrates produced by photosynthesis to be converted to energy. Ferreyra *et al.* 2010 demonstrated the impact oxygen levels had on potted tree growth with a 29% soil air capacity (Figure 10 - left) and a 7% soil air capacity example (Figure 10 - right). Root hypoxia (lack of oxygen) in avocados causes a reduction in canopy function (stomatal conductance, transpiration, assimilation), canopy growth and often causes leaf wilting as well as reduced root function leading to tree death (Schaffer *et al.* 2013).

Long-term (days) occurrence of root hypoxia significantly reduces stomatal conductance, increases ethylene levels in the leaf which lead to an increased incidence of leaf abscission. Short-term (90mins) shows no changes the Abscisic acid (ABA) concentrations associated as the biochemical signal for stomatal closure in plants subjected to root hypoxia. In fact, it is suggested that increased ABA concentrations in leaves may not be a signal for root hypoxia in avocados (Gil *et al.* 2009).

Over irrigation (120% of FAO crop evapotranspiration calculated tree water requirements) has been shown to reduce productivity in, on and off cropping years. Moreno-Ortega *et al.* 2019 suggested that supplying water over the tree water requirements calculated by the FAO-56 does not result in increased productivity.

7. Practical Considerations

Determining how much water and when to apply it to meet tree water requirements can be difficult. Research practices and results can assist in refining irrigation management.

7.1 Irrigation Scheduling

Changes in climatic conditions, tree physiology, phenology, and crop load etc., make it understandable why irrigating orchards by the calendar is not efficient irrigation management. Determining the threshold for irrigation volume was examined by Holzapfel *et al.* 2017 in a study that watered avocado trees at 25, 50, 75 and 100% of the reference evapotranspiration (ET_0) using a Class A evaporation pan. Results indicated that production and fruit size measurements increased noticeably up to 75% ET_0 but not beyond. The 75% ET_0 treatment was sufficient water application to wet the avocado rootzone to a depth of 90cm though ET_0 treatments less than 75% impacted the root's ability to access water (Figure 11). The 75% ET_0 treatment was never short of water.

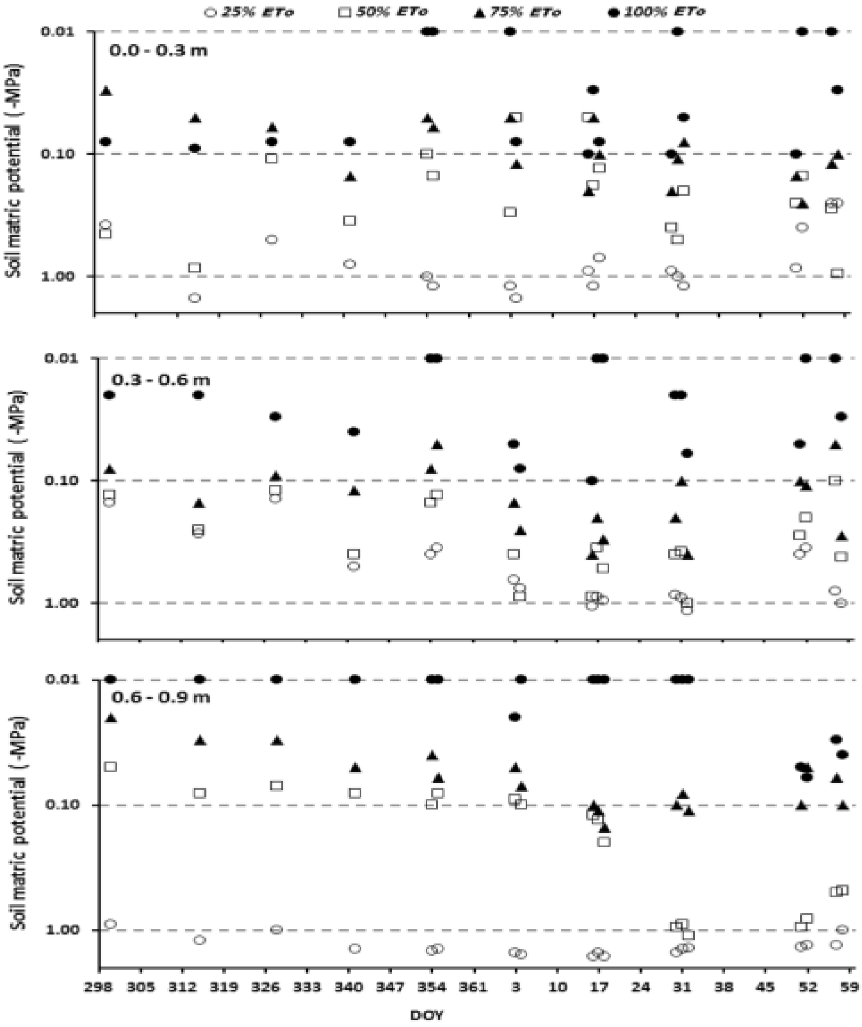


Figure 11 – Soil water potential at three different soil profile depths for 25, 50, 75 and 100% ET_0 water treatments (Class A evaporation pan) (Holzapfel *et al.* 2017). DOY = day of year.

Moreno – Ortega *et al.* 2019 however showed that marginal under-irrigating (80%) of FAO-56 crop evapotranspiration (ET_c) calculated tree water requirements resulted in yield reduction of 18% but fruit size and water productivity was similar to higher levels of water application (80% - 2.97kg / m3 vs 100% -2.92kg/m3).

Cantuarias 1995 illustrated that it was not just the volume of water applied but where it was applied that affected tree water status, transpiration rates and root growth. Trees with a bigger soil wetted volume transpired at a higher rate than those with a limited soil wetted volume (Figure 12). Frequency of irrigation here was 3 times a week for the one drip line which wetted approximately 25% of the soil volume and once a week for the five driplines which wetted approximately 75% of the soil volume and delivered a wetting pattern similar to a sprinkler.

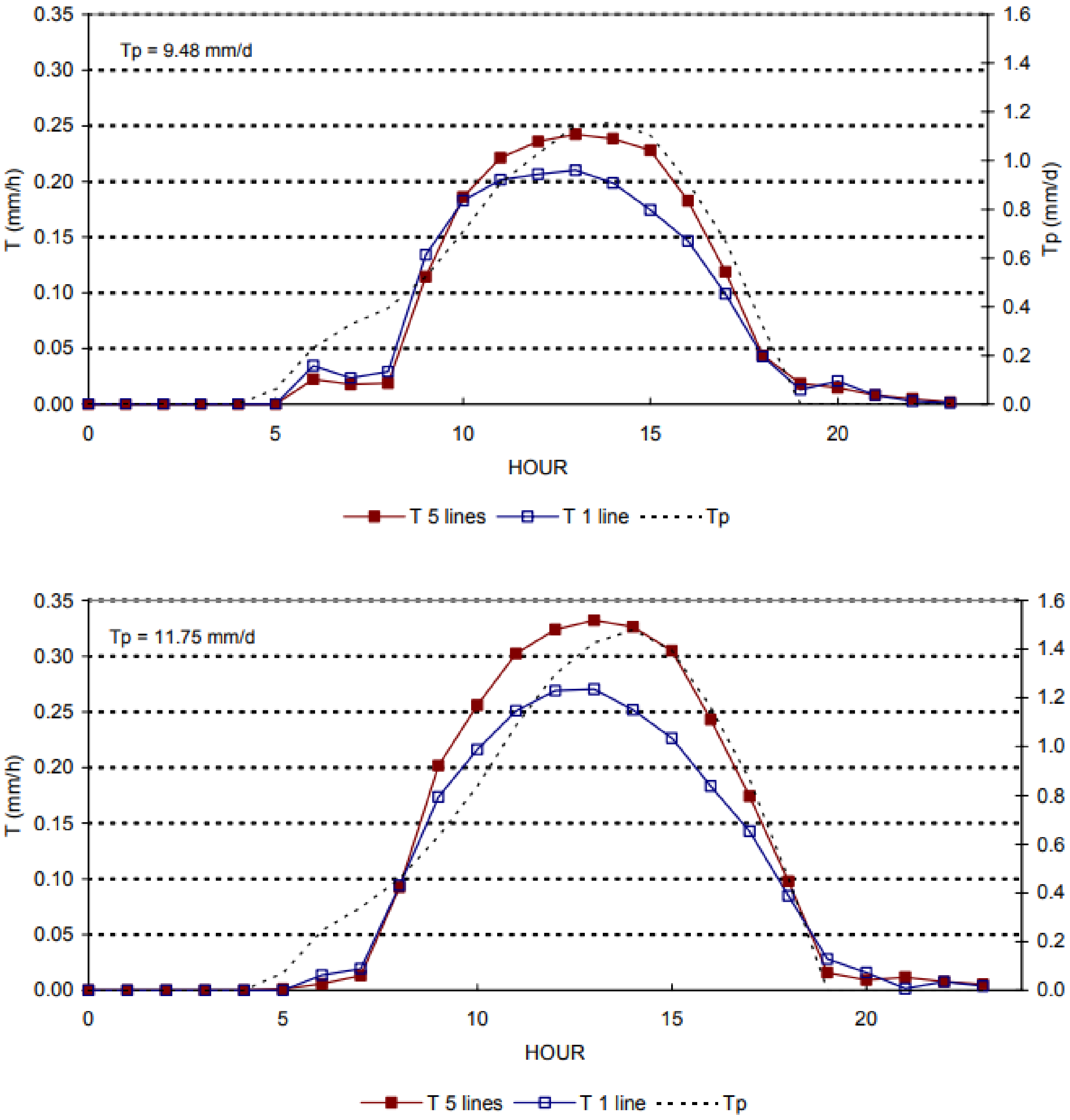


Figure 12 - Transpiration (mm/hr) of trees with different soil wetted volumes created by one dripline per tree versus 5 driplines per tree under low (Tp=9.48mm/d) and high evaporative demand (Tp=11.75mm/d) (Cantuarias 1995).

Maintaining moisture in a confined irrigation pattern does not encourage the tree to search for water outside of this zone (width and depth). Moreno – Ortega *et al.* 2019 determined that installing additional emitters in an already established wetted zone did not result in a bigger rootzone. It is possible that by increasing water supply to an already established wetted zone did not warrant a change in root distribution pattern, however changing the distribution of the established water volume may force these changes.

Timing of irrigation will impact the final fruit results (size and quality). Silber *et al.* 2011 found no clear impact of irrigation frequency on rootzone volume, flowering intensity or fruit set in the work they conducted manipulating drip irrigation frequency and root volume. They did however record that fruit drop (Figure 13a) was more intense the smaller the root volume (100L) and the longer the irrigation interval (every two days). Yield was impacted by irrigation interval and root volume in the same manner as fruit drop (Figure 13b). Interestingly Silber *et al.* 2011 considered daily irrigations moderate water stress and watering every second day a severe water stress treatment.

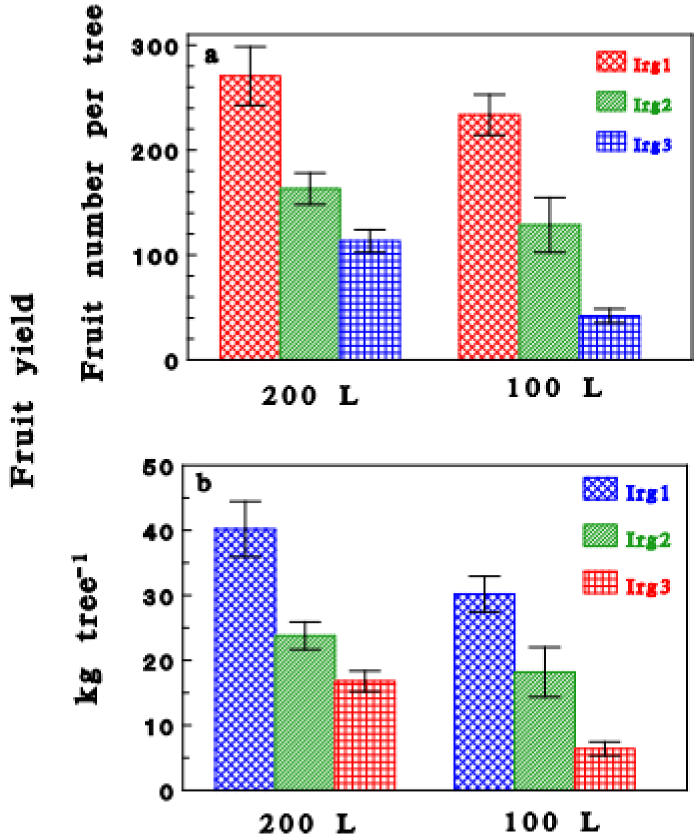


Figure 13 – Fruit yield of avocados subjected to two rootzone volumes and three irrigation treatments (Irg1 – pulse irrigation (15 min every 30 min) throughout the day and terminated at 17:00; Irg2 – one daily irrigation event terminated at 9:00; Irg3 - one irrigation event every two days terminated at 17:00 on the first day) a – number of fruit per tree and b – fruit weight per tree (Silber *et al.* 2011).

Moreno – Ortega *et al.* 2019 indicated that their second treatment (T2) supplied the seasonal tree water requirements as calculated by the FAO-56 crop transpiration method (8000m3 /ha producing 23t/ha in the on year and 13 t/ha in the off year). Yet as can be seen in Figure 14, T2 doesn't meet the calculated tree water requirement (dotted horizontal line) in the daily irrigated period for 2017/2018 or the tensiometer irrigation period for 2016/2017, though it is close. Totaling the volume applied does not necessarily mean the tree is receiving water when it is required.

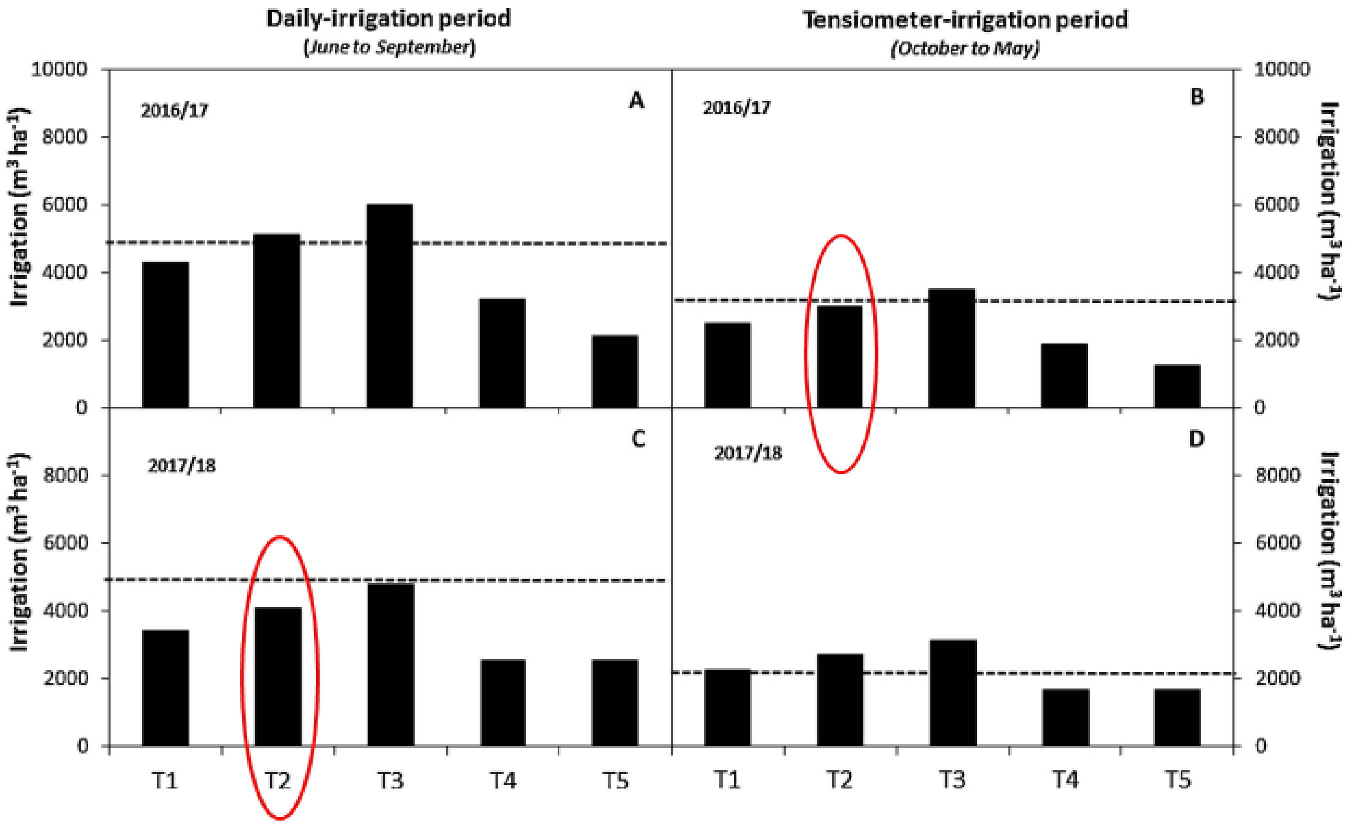


Figure 14 – Water supplied to avocado trees under different irrigation treatments. Treatment 2 (T2) is the calculated tree water requirements using the FAO-56 methodology (Moreno – Ortega *et al.* 2019).

Roets *et al.* 2013 described the importance of applying water in close consideration with tree phenology to develop water use trends that could be used for annual budgeting and adjusted for climatic conditions throughout the season (Figure 15). Cantuarias– Avilés 2019 determined that supplementary irrigation during winter resulted in increases in yield and fruit number per tree.

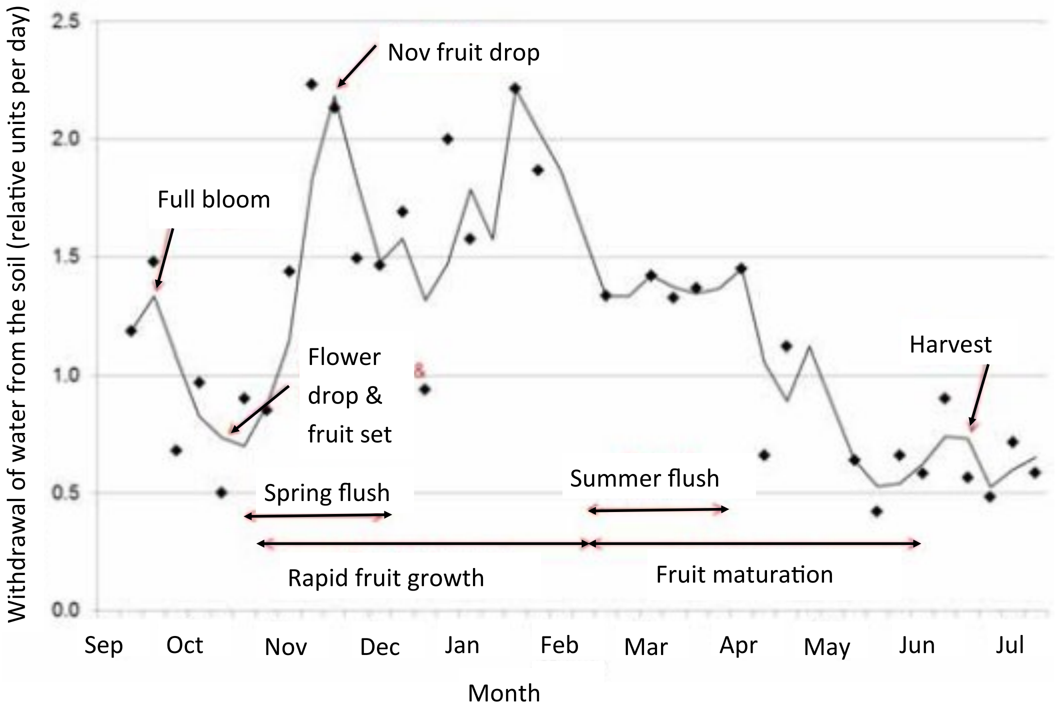


Figure 15 – Monthly soil water withdrawal in relation to avocado tree phenology - South Africa (Roets *et al.* 2013).

7.2 The Rootzone

The avocado rootzone is shallow and compact (30-60cm depth, 2m diameter around the trunk (Salgado & Cautin 2008), though roots have been found 1.3m from the soil surface in Western Australian sandy soils (Neuhaus *et al.* 2009). The small rootzone volume limits adequate water supply demanded by the tree during periods of high evaporative demand or times of critical growth (flowering, fruit set, seed development) (Silber *et al.* 2012).

An avocado root system consists of roots of various lengths / ages / health. During root flushes, new roots are replacing old or diseased roots and increasing surface area capacity for water and nutrient uptake. Root flushes form an alternating growth pattern with shoot flushes and fruit development, all of which are competing for available water and carbohydrate resources. Low water availability during root flush will slow root growth (Atkinson 1980) with extended dry periods shown to reduce surface root length density by approximately 25% (Neuhaus *et al.* 2009).

The majority of feeder roots are found in the top 60cm of soil and grow into the natural litter layer produced by the tree (Carr 2013). Avocado roots are considered highly suberized (not white roots), which means that they have a barrier that impedes water and solute transport into the root. Doupis *et al.* 2017 described them as having low hydraulic conductivity, high oxygen demand and poor water uptake efficiency making water management strategies specific to root capacity essential for efficient use of water.

Root growth is related to soil temperature. Whiley *et al.* 1990a suggested avocado roots grew between 18-28°C and root growth was reduced below 13°C and above 32°C. Cantuarias 1995 observed optimal root growth between approximately 20-22°C (Figure 16). Lahav and Trochoulias 1982 suggested day / night temperatures of 37/30 (°C) reduced root growth and under such conditions, soil cooling was required.

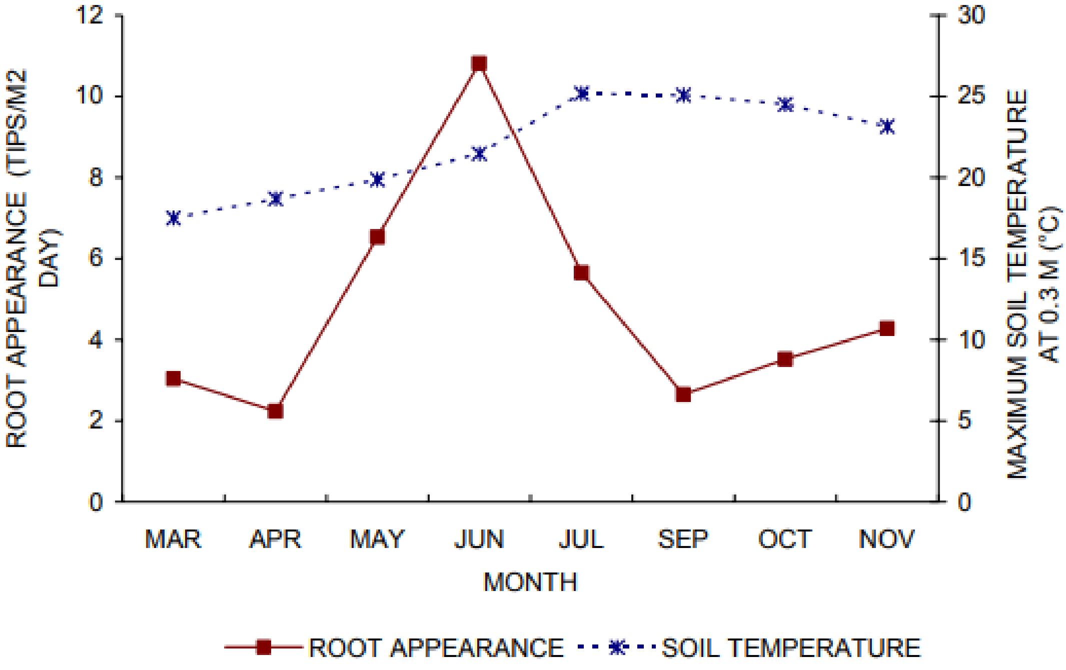


Figure 16 – Avocado root growth versus soil temperature (Cantuarias 1995).

Burgis and Wolfe demonstrated in 1945 that avocado roots don't have the root hair adaptation increasing the soil surface area in which the tree can access moisture and nutrients, though beneficial relationships with mycorrhizae fungi have been reported improving access to soil water and nutrient resources (Lahav *et al.* 2013).

Differences in avocado xylem design has implications for tree water use efficiency and rootstock selection. Fassio *et al.* 2009 reported Duke 7 to have a 29% higher sap flow rate (and transpiration) than Toro Canyon due to differences in root xylem vessel and root design (Figure 17). Duke 7 had finer roots.

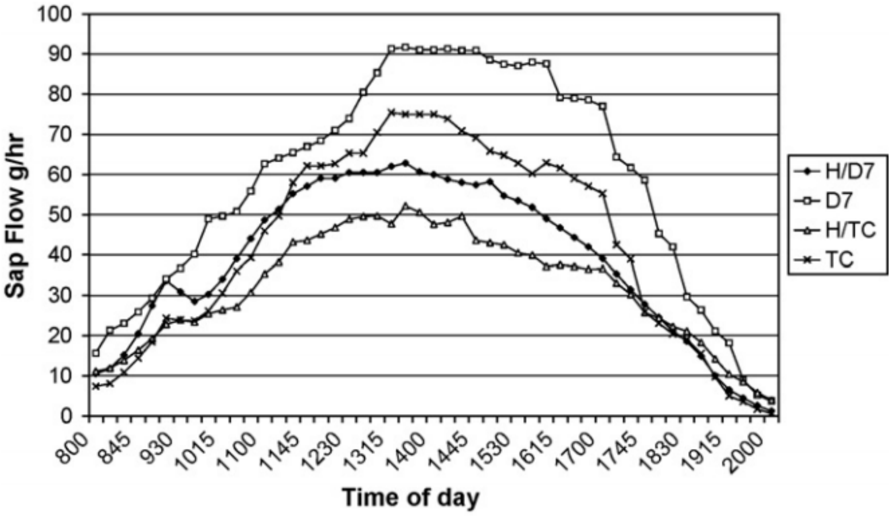


Figure 17 – Sap flow (g/hr) of 'Hass' trees grafted on Duke 7 rootstock (H/D7), Duke 7 on own roots (D7), 'Hass' trees grafted on Toro Canyon rootstock (H/TC) and Toro Canyon on own roots (TC), (Fassio *et al.* 2009).

Root health is important in maintaining water uptake and transpiration. Weak root systems (e.g. growth, disease, rots, oxygen levels) can inhibit the volume of water available to the tree despite soil moisture availability. This will impact nutrient uptake, photosynthesis and energy required to maximise fruit yield and quality outcomes (Ferreyra *et al.* 2010). Ferreyra *et al.* 2007 reported that porous soils with 30% air volume were optimal for avocado production but anything less than 17% soil air capacity would result in root oxygen deprivation (hypoxia).

Cantuarias 1995 demonstrated that root growth follows the pattern of the irrigated wetted zone (Figure 18) in a study examining water distribution. A greater distribution of active roots was seen in the larger soil wetted volume created by 5 driplines and also at soil depth.

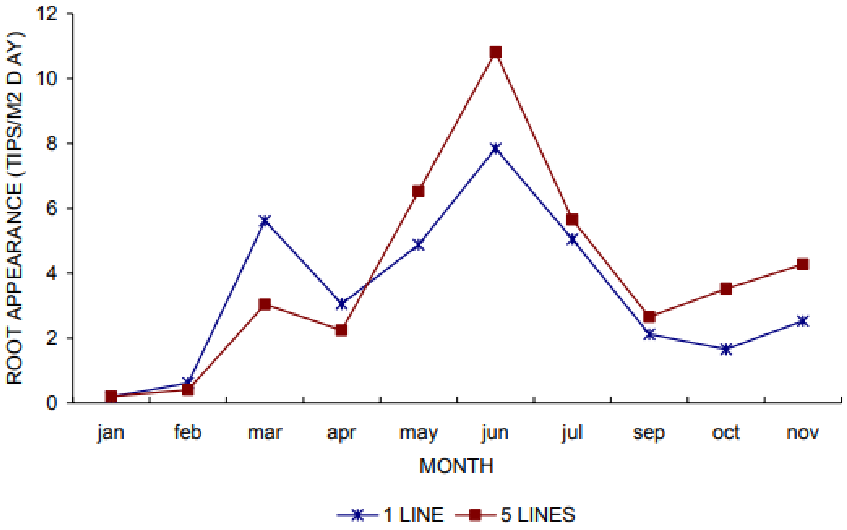


Figure 18 - Root tip appearance under one drip line versus five drip lines per tree (Cantuarias 1995).

Avocado root distribution can also be influenced by competition with other orchard vegetation for soil space and resources. Root distribution under three different ground cover management systems on mounded trees (bare ground, vegetative strip, and total groundcover) was shown to change at different depths (Atucha *et al.* 2013, Figure 19). The results indicated that the bare ground provided no competition for soil space or resources with other roots and therefore the number of roots present at each depth of the soil profile was uniform. The presence of vegetation as either a strip or total groundcover however changed the root distribution reducing the number of avocado roots seen in the top 30cm and making the primary avocado root zone between 30-60cm. This has implications for irrigating to ensure that the water applied is making it down to this zone continuously and not just during deeper irrigation events.

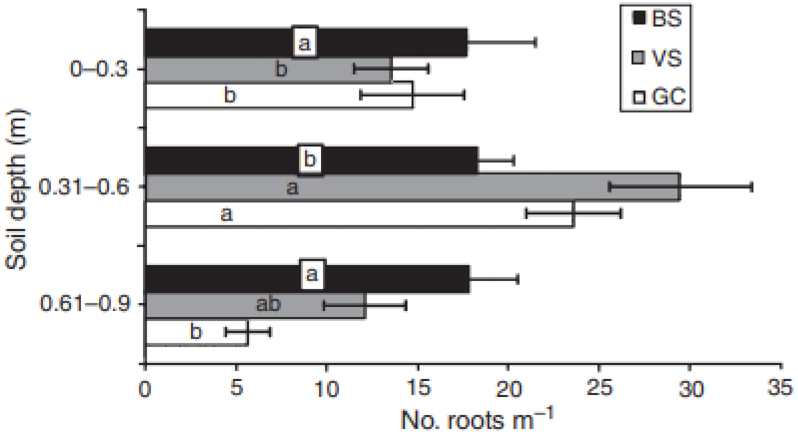


Figure 19 – Depth distribution of avocado roots at 0-0.3m, 0.31-0.6m and 0.61-0.9m for bare soil (BS), vegetative strip (VS) and ground cover (GC) treatments (Atucha *et al.* 2013).

Irrigation efficiency will be dependent on the health and volume of active roots. Chilean based research conducted by Atucha *et al.* 2013 reported two distinct root flushes in young non-bearing trees (2009-10) but only one significant spring-based flush in bearing trees (2010-11) (Figure 20). Not only is there a change in the root flush pattern directly related to competition with fruit / vegetative flushes for water and carbohydrate / nutrient resources, but the volume of new roots has drastically diminished. Given the primary focus of avocado production is fruit yield, size and quality, ensuring that water and nutrient demands during root flushes are met will be beneficial to achieving seasonal objectives.

Roots are the primary conductor of water and nutrients to the tree and their ability to function at maximum capacity is going to relate to root diameter and lifespan. Atucha *et al.* 2013 also demonstrated that roots grown under bare soil conditions were about 50/50, fine versus bigger root diameters, yet the majority of roots competing for soil space and resources in the vegetative strip and total groundcover had a smaller diameter (Figure 21) . Finer roots are less subersized and thus conduct water better than roots with larger diameters providing the tree with the opportunity to adapt to more challenging dryer environments, though the finer roots had a shorter lifespan. Roots grown under the hotter summer soil temperatures in combination with competition for resources were also observed to have a shorter lifespan than those grown in the cooler spring flush.

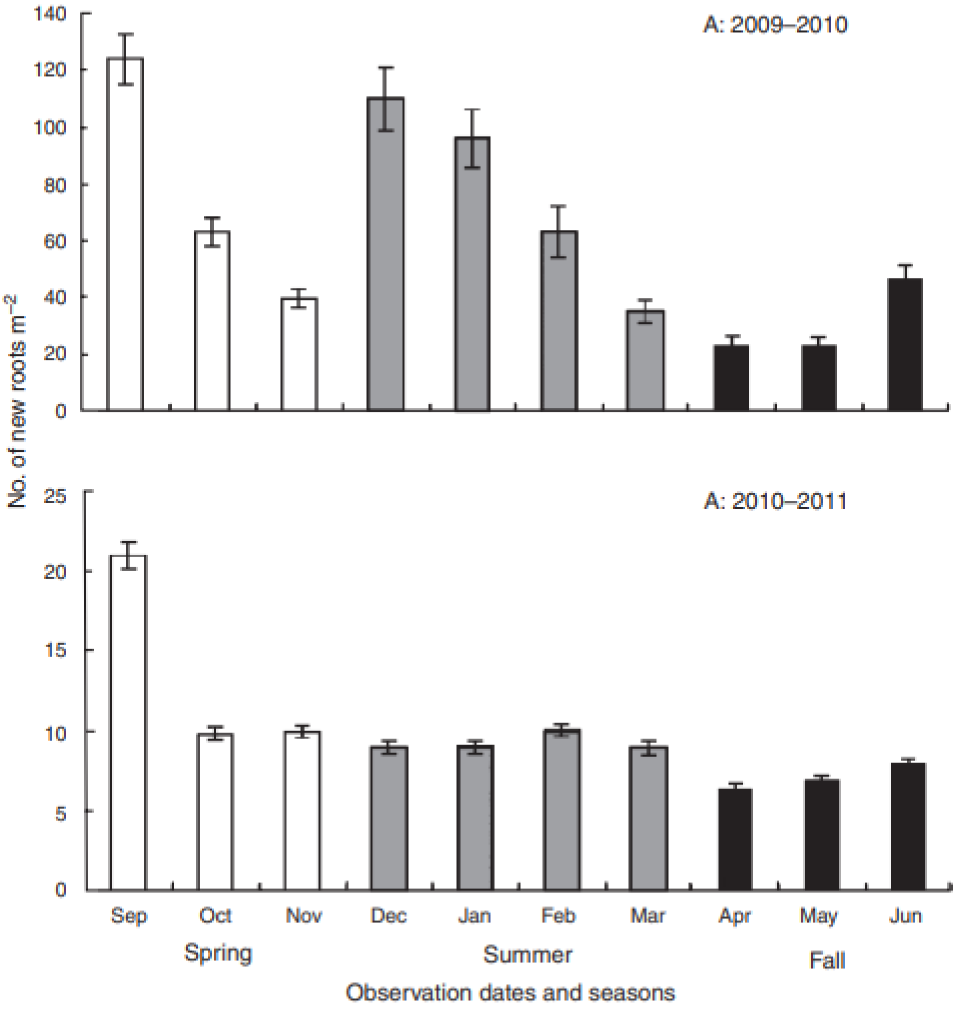


Figure 20 – Number of new avocado roots observed in non-bearing trees (2009-2010) and in bearing trees (2010-2011) (Atucha *et al.* 2013). Different coloured bars represent seasons.

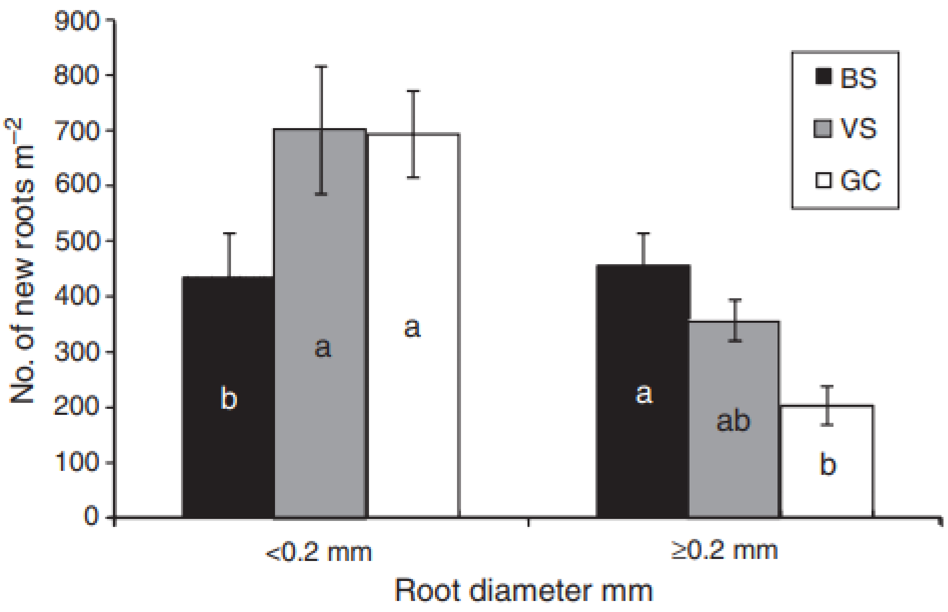


Figure 21 – Number of avocado roots per metre square <0.2mm and ≥0.2mm diameter for bare soil (BS), vegetative strip (VS) and ground cover (GC) treatments (Atucha *et al.* 2013).

Making a choice between sprinklers versus drip is a big question, especially when installing irrigation in mature orchards located in traditionally rainfed environments; considering wetting patterns (Figure 22) and existing rootzone. Salgado & Cautin 2008 examined avocado root distribution in fine and coarse textured soils under drip and sprinkler irrigation. They reported 25% more roots in the fine soil/drip irrigated treatment while root occurrence in the drip / coarse soil or under sprinklers regardless of soil type were all very similar.

Darwish & Elmetwalli 2019 showed in their study that rather than having drip or sprinklers, a combination of the two systems resulted in better fruit yields and was theorised to have resulted from a more distributed and enhanced root system.

Figure 22 - Irrigation distribution under drip *(left)* and sprinkler systems *(right)* (Wehr & Smith 2016)

7.3 Trunks, stems, leaves

Mature avocado leaves have a waxy cuticle that covers both sides and the young leaves are covered in a dense soft down, reducing water loss from the leaf surface area. (Blanke & Lovatt 1993, Whiley *et al.* 1988).

Sap flow and transpiration have been positively corelated (Figure 23 - Cantuarias 1995), indicating that the volume and speed of sap flow within an avocado tree (in xylem of stems and trunk) will impact the rate and volume of transpiration and thus the need to replenish water used. Cantuarias 1995 measured sap flow in an avocado tree at speeds of 30-35cm/hr.

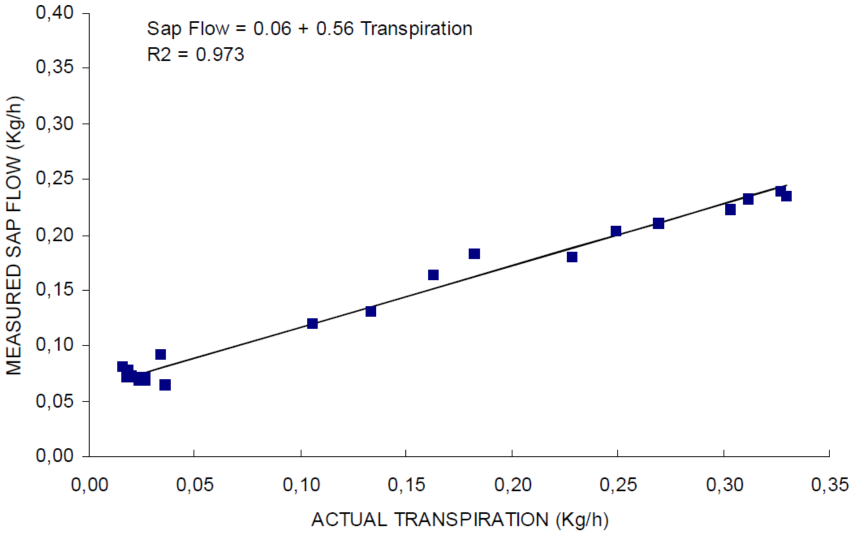


Figure 23 – Relationship between sap flow and transpiration (Cantuarias 1995).

Water is not an unlimited resource and the tree sends signals to close the stomatal pores (Figure 24) occurring on the lower side of leaves (35,000-51,000cm^{-2} Blanke & Lovatt, 1993) to reduce transpiration and conserve moisture.

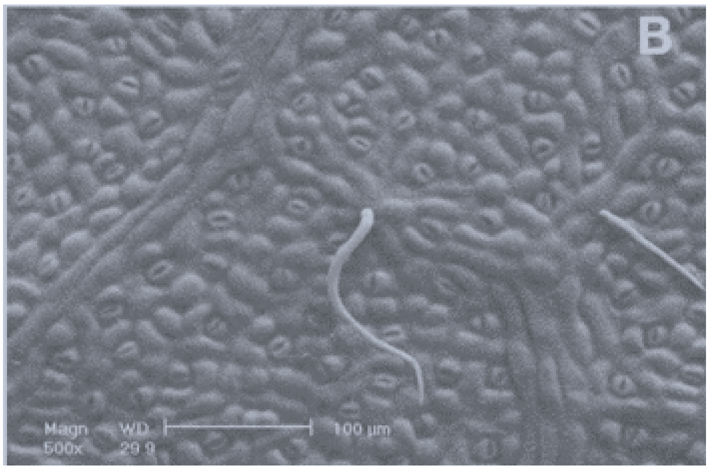


Figure 24 – Stomata on the lower side of an avocado leaf (Mickelbart *et al.* 2000).

Scholefield and Kridedemann 1979 showed that young leaves could not control stomata until leaves reached 90% of their mature size. Given Hass leaves have been reported to take 30 days to reach mature size from bud break (Pongsomboon *et al.* 1997), trees will have a higher water requirement during periods of leaf flush to avoid wilting in the new growth and maintaining whole tree water balance. Eighty percent of stomata on old leaves were closed indicating declining activity with age (Whiley *et al.* 1988). Stomatal conductance decreases with a reduction of leaf water potential below -0.4MPa and ceases with stomata closure at -1.0 to -1.2MPa (Carr 2013).

Stomatal conductance is important for canopy cooling. When the tree is actively transpiring, an evaporative cooling process is occurring, however when stomata close, this process slows or ceases causing the tree temperature to increase impacting tree physiological function, fruit size and quality.

Cantuarias 1995 illustrates how water distribution supplied by five driplines reduces canopy temperature below air temperature in the hottest part of the day on both a day of low evaporative demand (Tp=9.15mm/d) to a day of high evaporative demand (Tp=11.33mm/d) (Figure 25). Under high evaporative demand ((Tp=11.33mm/d), the single drip line cannot supply enough water to reduce the canopy temperature below the air temperature.

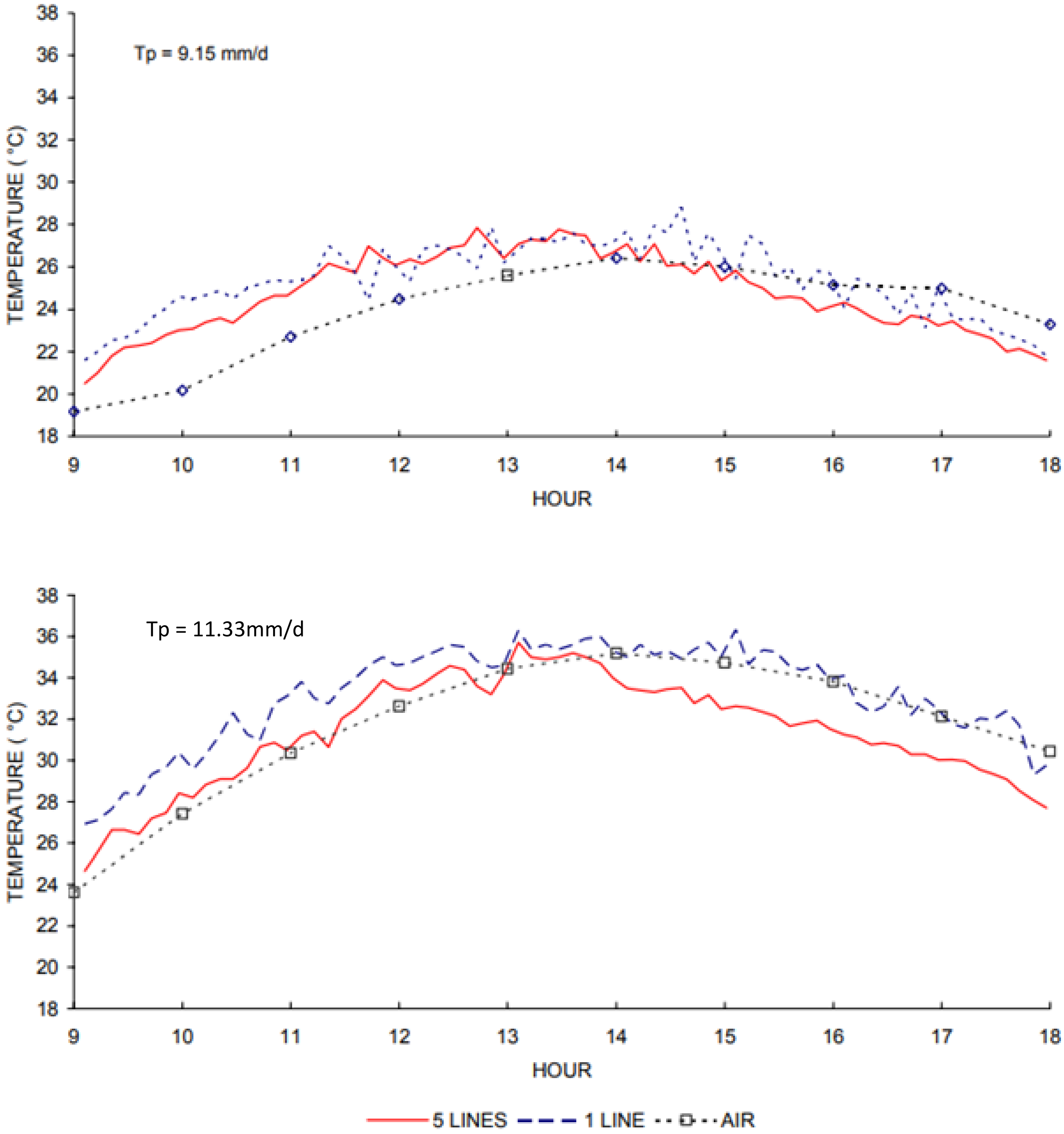


Figure 25 – The relationship of canopy and air temperature under two different drip irrigation treatments (5 driplines per avocado tree versus 1) on a day of low evaporative demand (Tp=9.15mm/d)(top) and on a day of high evaporative demand (Tp=11.33mm/d)(bottom) (Cantuarias 1995).

Stomates open and close in response to changes in the surrounding environment and tree water requirements. In mature leaves, stomatal closure has been illustrated by Whiley *et al.* 1988 in response to temperature (approx. 24°C), high irradiance (approx. 1.8 PAR) and Vapour Pressure Deficit (VPD – approx. 1·5 kPa) at midday. Factors that affect moisture loss through stomata include:

1. **Temperature** – As leaf temperature increases, so does evaporation of moisture from the stomata. An educated guess is between 25-30°C for avocado stomatal decline on temperature alone (Schofield *et al.* 1980, Whiley *et al.* 1988). Figure 26 illustrates a temperature within the suggested range for maximum transpiration rates (Roets *et al.* 2013).

2. **Humidity** – The level of moisture in the air surrounding the leaf impacts the level of stomatal activity. Heath *et al.* 2004 reported excessive water loss from leaves under low humidity conditions especially in the morning when stomata are fully open, while Roets *et al.* 2013 (Figure 27) illustrates a decline in transpiration as the moisture in the air increases is also relevant.

3. **Windy weather** – The speed at which air moves across the surface of the leaf will impact water loss and stomatal activity. Heath *et al.* 2003 demonstrated that a wind speed of 6mph (9.65km/hr) across avocados leaves increased sap flow and transpiration by 31%.

4. **Light** – The information about the impact of light on stomatal activity is conflicting. Avocados evolved as understory rainforest trees and therefore in some growing environments, high light levels result in light and heat damage for both trees and fruit. Stomata have been shown to behave similarly in light and dark situations (Pongsomboon *et al.* 1997) though it has been reported that stomata of mature leaves close in the dark (Scholefield & Kriedemann 1979). Stomatal conductance was higher in non-bearing shaded leaves (maximum conductance at approximately 1000 µmole m-2s-1) than leaves in full sun (Silber *et al.* 2013).

5. **Soil moisture availability (high and low)** - Stomatal conductance has been suggested as a sensitive indicator of water stress for avocado trees (Neuhaus *et al.* 2007).

6. **Canopy size** impacts the number of leaves present and the surface area from which water can be lost. The relationship between leaf area and sap flow, thus transpiration and water loss has been shown to be highly related (Kaneko 2016) (Figure 28).

7. **Vapour-pressure deficit** (VPD), is the difference (*deficit*) between the actual air moisture and how much moisture the air can hold when it is saturated at a specific temperature (Yuan *et al.* 2019). In relation to plants, VPD is the difference in vapour pressure (moisture content) between the inside of the avocado leaf and the atmosphere outside the leaf. VPD is an important measure in greenhouse production. Increasing VPD results in increases in transpiration and then stomatal closure to save water (Grossiord *et al.* 2020). Stomatal closure in avocados was predicted by Pongsomboon *et al.* 1997 to be dependent more on VPD than being affected by other environmental factors such as temperature. Relative humidity is the ratio of actual water vapour pressure to saturated water vapour pressure in the atmosphere; could this measurement transfer some indications for VPD changes in avocado trees?

It is important to note that one factor is unlikely to work independently of the others and the closing of stomata will lead to reduced photosynthetic capacity and the ability to produce energy and carbohydrates.

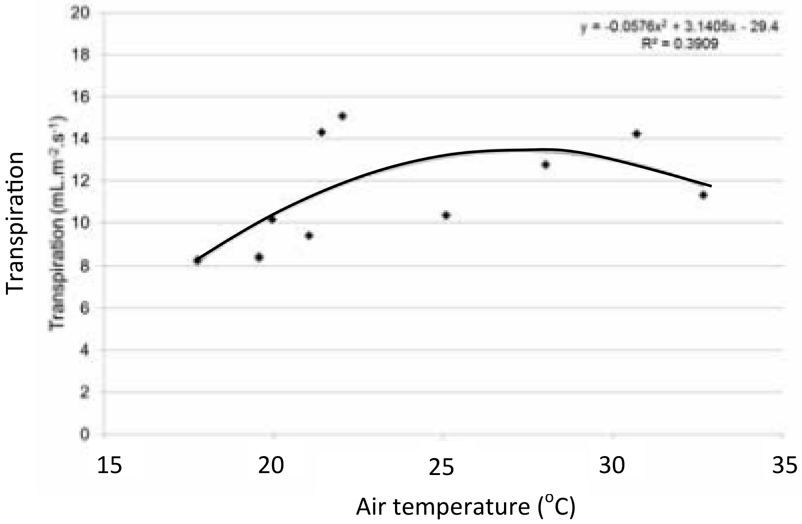


Figure 26 – Relationship between avocado transpiration and air temperature (Roets *et al.* 2013).

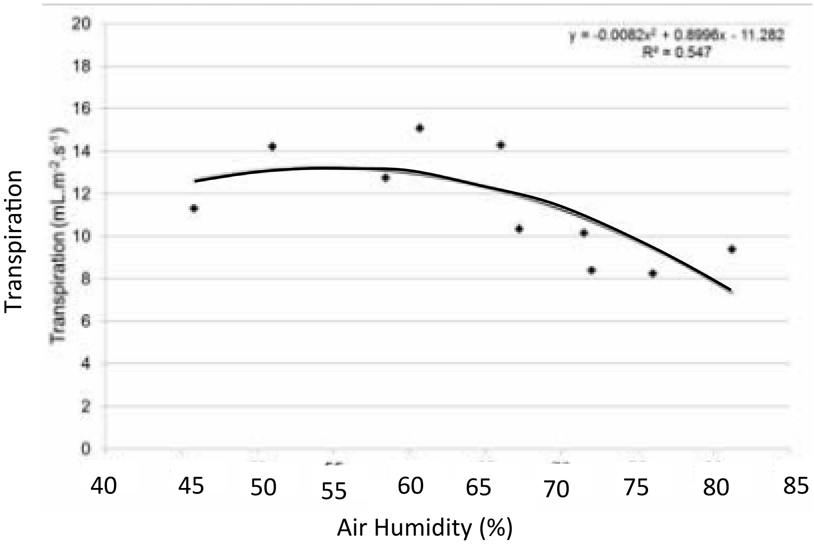


Figure 27 – Relationship between avocado transpiration and air humidity (Roets *et al.* 2013).

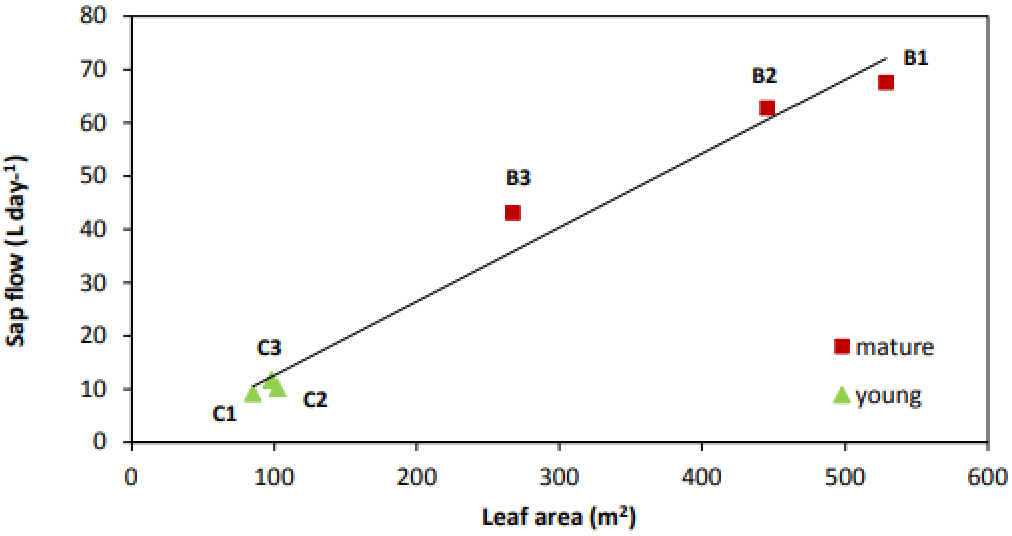


Figure 28 – Relationship between leaf area and sap flow for both mature and young trees in New Zealand July 2015 (Kaneko 2016).

7.4 Flowering

Avocado trees produce millions of flowers annually with approximately 1.3 million flowers, buds and fruitlets abscised annually per tree and only approximately 1% of fruit reaching the harvest stage (Lahav & Zamet 1999). Stomata are present in low density on the lower side of sepals and petals.

Avocado flowers increase the surface area for water loss, they have a high transpiration rate and water availability must be optimal for proper fruit set to occur. Flowers can account for approximately 13% of tree water use (total transpiration) during flowering (Whiley *et al.* 1988). Kaneko 2016 recorded a higher crop coefficient (K_c = 0.6) during flowering than the following month (K_c=0.45) in New Zealand but in Australia under dry warm conditions could the Kc during flowering could be higher again?

The water availability domino effect described in Figure 2 may have a significant impact during flowering and fruit set. A shortage of carbohydrates during this time may affect ovary development and fruit reaching maturity. This can be exacerbated by local environmental conditions and low root activity determining whether water supplied to the tree meets demand.

High starch levels within the flower style have been reported to promote fruit set, while those with lower levels abscised (Figure 29 - Alcaraz *et al.* 2013). Understanding bud development better and the role of irrigation pre-flowering may assist in improving carbohydrate levels to set and hold fruit. Supporting early flower onset with irrigation may also be beneficial to fruit set with early flowers shown to have higher carbohydrate levels and thus a better chance of setting fruit and maintaining them till maturity (Figure 30 - Alcaraz *et al.* 2013).

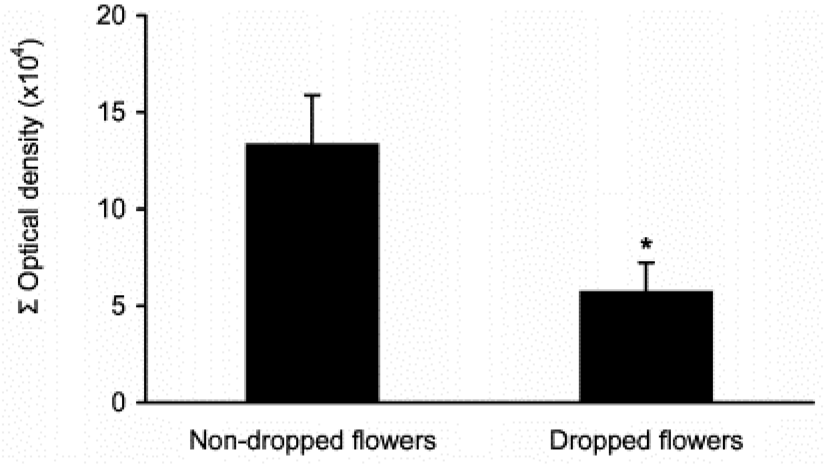


Figure 29 – Starch content and reproductive success (Alcaraz *et al.* 2013). Starch content in the style in two populations of flowers; those that dropped and those that remained in the trees until harvest in 'Hass' avocado.

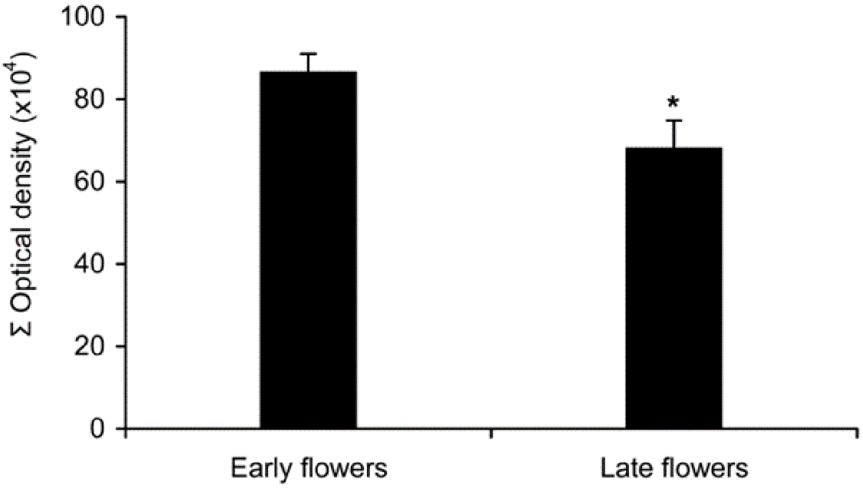


Figure 30 – Starch content in early and late flowers (Alcaraz *et al.* 2013). Starch content in the ovary of flowers from early developing inflorescences compared with that of flowers from a group of late developing inflorescences that open around a month later and usually do not produce fruits in 'Hass' avocado.

7.5 Fruit development

Avocado fruit has a skin, thick fleshy mesocarp, a large seed and an oil content of approximately 17% (Wolstenholme 1987, Lui *et al.* 1999).

The fruit grows and develops in two distinct growth phases forming a "S" shaped curve (Figure 31). Rapid cell division and sugar accumulation dominates the initial growth phase followed by cell expansion and oil accumulation (Lui *et al.* 1999), though it has been reported that the fruit continues a level of cell division throughout fruit growth (Scora *et al.* 2002, Schroeder 1958)

Both the seed and oil content have a high priority for carbohydrates (Wolstenholme 1987), which may become depleted under low water availability, the closure of stomata and reduced photosynthetic function.

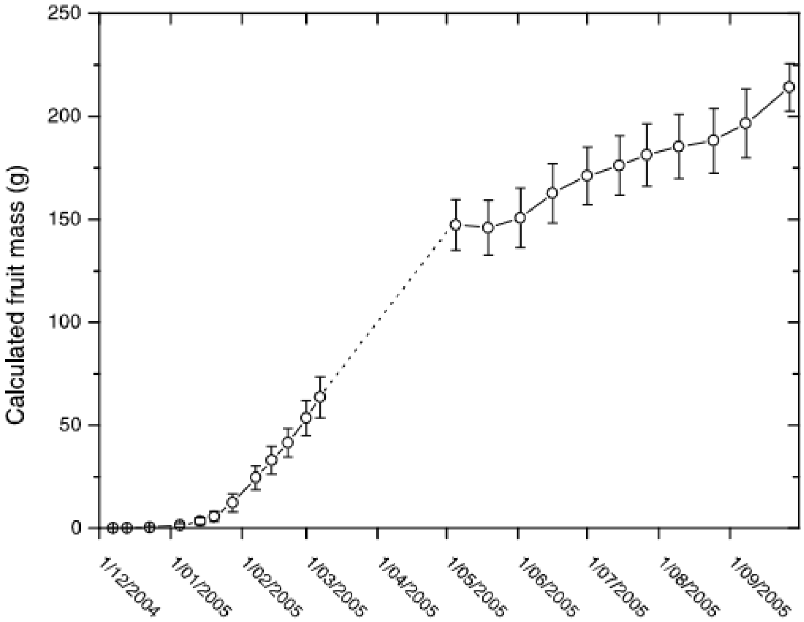


Figure 31 – Avocado fruit growth curve illustrating the initial fast growth stage followed by the linear growth phase (Dixon *et al.* 2006).

Young fruit like leaves also have stomata (50-75/mm^{-2} Whiley *et al.* 1988). The transpiration rates of young fruit exceed both sepals/petals and leaves (Sepals/petals > leaves (Whiley *et al.* 1988)). As fruit develops it becomes coated with a wax layer which blocks the stomata. These pores are then termed lenticels.

Fruit growth and development is closely linked to the water status of the tree. A lack of water during the first fast growth phase will impact final fruit size and the volume of harvestable fruit (Figure 32). In some NZ work, trees subjected to drought conditions showed higher fruit abscission rates in the three months following flowering, lighter crops and smaller fruit (Kaneko 2016). Fruit size and yield cannot be recovered through the application of water in the second growth stage if the first growth stage has undergone moisture stress (Kaneko 2016).

Schroeder & Wieland demonstrated in 1956 that as the tree experienced moisture stress, water was moved from the fruit to the leaves causing the fruit to shrink. Turgor pressure drives cell expansion and therefore water deficit will have a significant impact on the development of all primary growth organs (i.e. flush, fruit, roots) (Silber *et al.* 2013). Daily tree water status will impact the growth / shrinkage cycle and final fruit size.

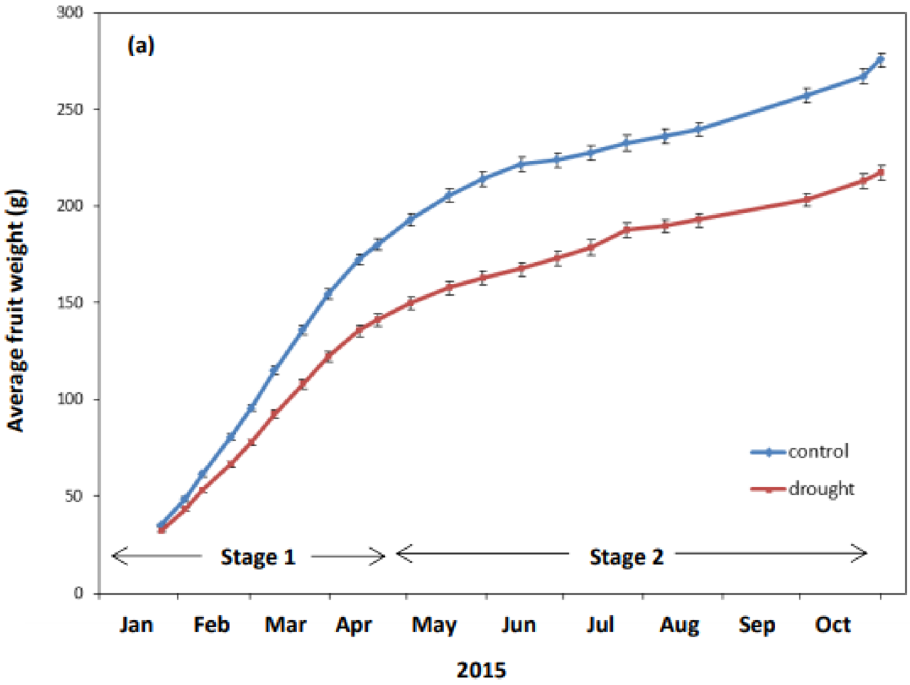


Figure 32 – Average fruit weight (g) of 'Hass' avocado well-watered control trees versus trees subjected to drought conditions (Kaneko 2016).

Avocado fruit size and weight decreases with increased production and the total yield of an avocado tree is strongly related to the number of fruits per tree (Michelakis *et al.* 1993). Kaneko 2016 illustrated this in Figure 33.

Water deficits result in fruit drop generally between fruit set and 50% of the fruits final size (Ferreyra & Selles 2012) Trees often set more fruit than they can support and adjust the crop load within a month of fruit set and again in early summer (Schaffer *et al.* 2013). Providing adequate water at the beginning of summer was Lahav and Whiley's (2002) answer for reducing fruit drop during this high climatic stress period.

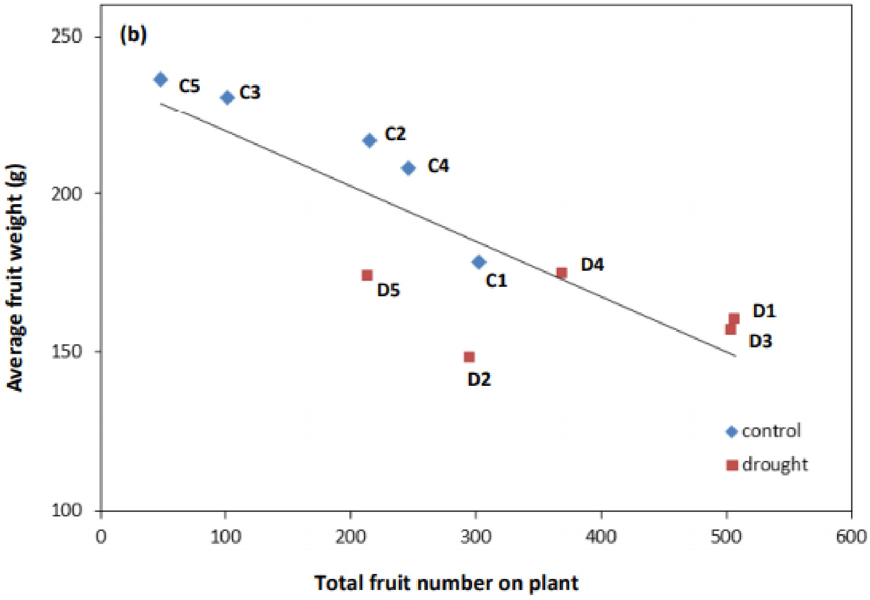


Figure 33 – Relationship between fruit weight and total yield (Kaneko 2016).

Avocado fruit will not ripen while still hanging on the tree (Scora *et al.* 2002), yet water stress in the later stages of fruit growth will negatively impact fruit quality. Water stress during critical phenological growth stages have been linked to fruit quality issues postharvest and disorders such as ring-neck and internal browning etc. (Schaffer *et al.* 2013).

Dry matter and oil content of drought treated trees (Figure 34) was also lower than the non-stressed trees though both reached the required level for harvest (NZ-24% dry matter) (Kaneko 2016). Given that moisture % and oil content (Figure 35) are highly correlated and this is related to the fruit quality parameter of days to ripen (Figure 36), the importance of irrigation at the correct time is significant (Bezuidenhout & Bezuidenhout 2014). Neuhaus *et al.* 2009 determined that total soil drying caused a reduction in fruit water content of 20%, this is substantial when considering final yields.

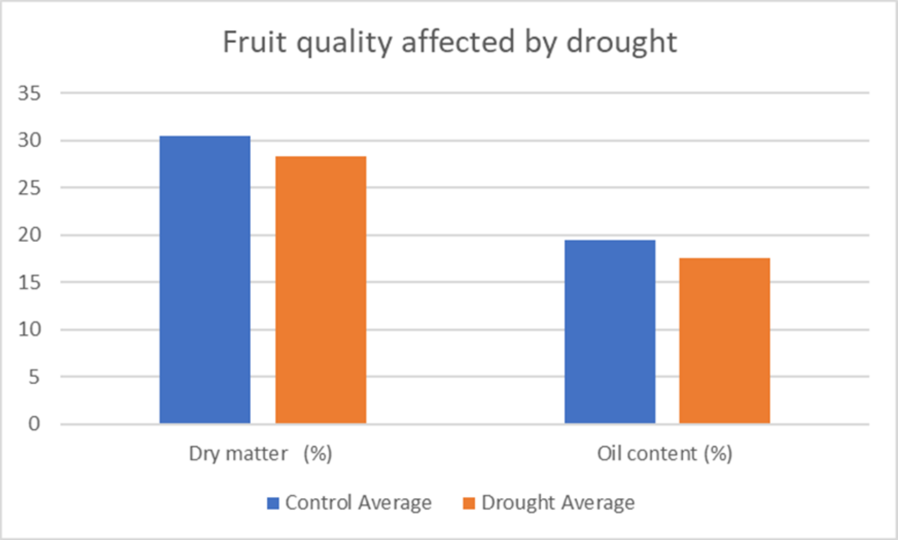


Figure 34 – Fruit quality parameters, dry matter (%) and oil content (%) as affected by drought (Kaneko 2016).

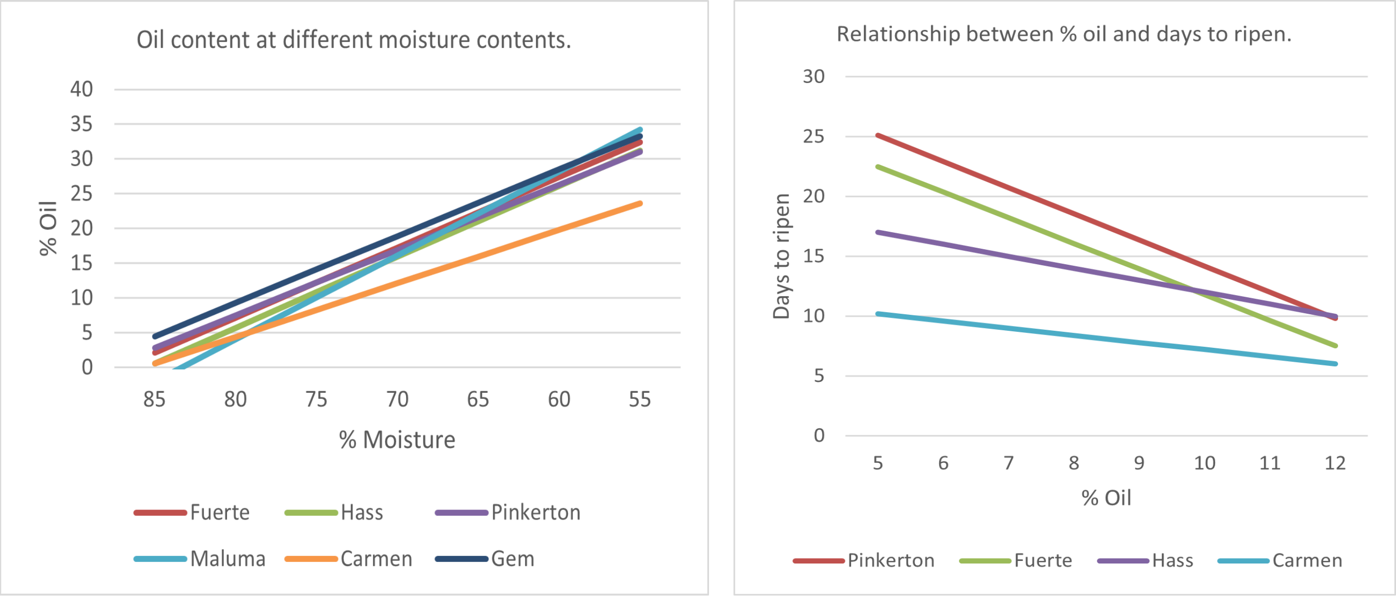


Figure 35 (above left) – Oil content at different moisture contents for different avocado varieties (Bezuidenhout & Bezuidenhout 2014).

Figure 36 (above right) – Relationship between oil content and days to ripen for different avocado varieties (Bezuidenhout & Bezuidenhout 2014).

Holzapfel *et al.* 2017 measured fruit size as part of their irrigation study (25%, 50%, 75% & 100% of ET_0) and demonstrated that irrigation volume positively affected fruit length (polar) and diameter (equatorial) (Figure 37). Michelakis *et al.* 1993 recorded no difference in fruit weight or oil content with his 30%, 60% and 90% pan evaporation study but found like Holzapfel *et al.* 2017 who recommended water application of 75% ET_0 and above that the 30% treatment produced the lowest yield and that there was no difference in yield between the 60% and 90% treatments.

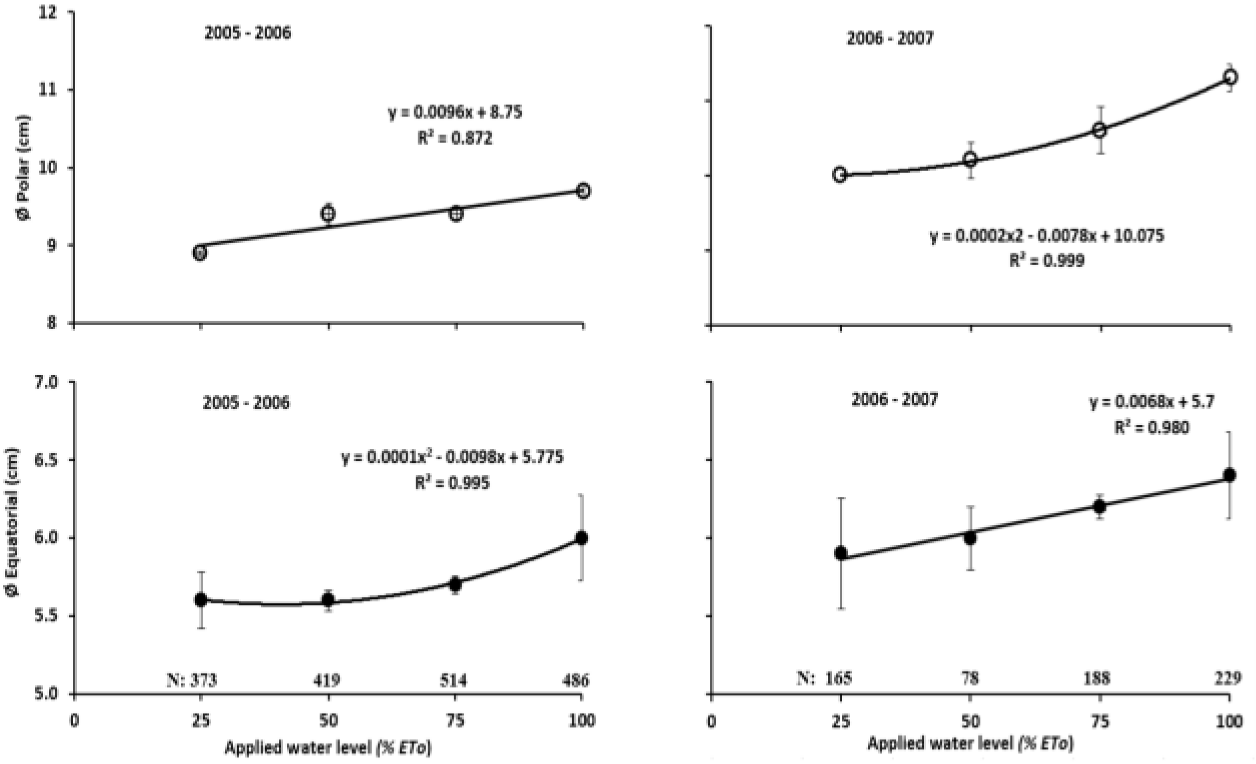


Figure 37 – Avocado polar and equatorial diameters at harvest for ET_0 applied water level treatments (25, 50, 75, 100%) during the 2005-2006 (on-crop) and 2006-2007 (off-crop) seasons (Holzapfel *et al.* 2017). ET_0 is estimated reference evapotranspiration using a Class A evaporation pan. N = number of trees assessed .

During fruit and seed development the carbohydrates allocated to the roots for growth and activity are diverted to the sink, reducing the ability to supply water (and nutrients) when the tree needs it the most (Whiley & Wolstenholme 1990b). The work conducted by Silber *et al.* 2011 suggests that increasing water availability through though this period would benefit water uptake, fruit development and retention. In fact, while figures were not published Silber *et al.* 2011 reported that increased water availability through pulse drip irrigation (15minutes every 30 minutes from 1am till 5pm) increased the amount of energy that the tree produced during periods of fruit growth. Increasing irrigation frequency was shown to improve vegetative status and was linked to the importance of water in cell division, cell enlargement, metabolic activities and nutrient delivery (Ouma 2007).

7.6 Nutrition and Soil Biology

Irrigation and nutrition are mutually dependent, therefore management of these two aspects need to be considered together for optimal results (Silber *et al.* 2019). Water is required in the rootzone for nutrients to be soluble and available for uptake by avocado roots. Irrigation provides the opportunity to influence soluble nutrients availability in the soil profile and to add fertilisers to the irrigation water for direct delivery to the avocado rootzone (fertigation). Infrastructure, irrigation type (sprinkler v/s drip), water quality and water volume applied will impact the timing and distribution (width & depth) of nutrients supplied by fertigation. Nutrition in relation to irrigation is not about how much fertiliser to put on and when but what happens to nutrients in the soil solution created by irrigation events.

Potassium is particularly important for turgor pressure or the movement of water in plant cells and many nutrients including calcium move throughout the plant in the sap flow powered by transpiration. Low water availability will reduce the trees ability to access nutrients from the soil and could be made worse by the high presence of salts.

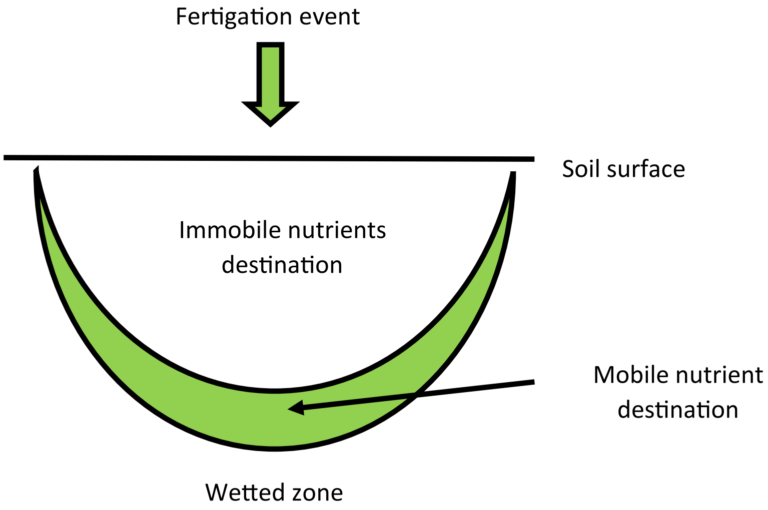
Fertilisers are made up of elements that disassociate into cations and anions when dissolved in water (Figure 38). ‘Cations’ are positively charged, and ‘anions’ are negatively charged.

Cations		Anions	
NH_4^+	Ammonium	NO_3^-	Nitrate
K^+	Potassium	Cl^-	Chloride
Na^+	Sodium	SO_4^{2-}	Sulphate
Ca^{2+}	Calcium	$H_2PO_4^-$ / HPO_4^{2-}	Phosphate
Mg^{2+}	Magnesium	MoO_4^{2-}	Molybdate
Zn^{2+}	Zinc	BO_3^{3-}	Boron
Mn^{2+}	Manganese		
Fe^{2+}	Iron		
Cu^{2+}	Copper		

Figure 38 – Common cation and anions in soil.

When fertigated irrigation water is added to the soil, it travels via mass flow towards the roots for use by the tree. Nutrients in soil solution that are not used by the tree are attracted to soil colloids which are negatively charged and attract positive cations; undergo a chemical reaction with another element to become a solid (e.g. Calcium and Phosphorous = Calcium Phosphate); can become fixed and unavailable due to soil pH; or are negatively charged or highly mobile like nitrate and can be leached from soil profile with draining water.

Nutrient mobility (Figure 39) in soils is a particular consideration with irrigation because it will determine the distribution of mobile nutrients in the soil profile.



Mobile	Partially	Immobile
Nitrate	Ammonium	Organic N
Sulfur	Potassium	Phosphorous
Boron	Calcium	Iron
Manganese	Molybdenum	Magnesium
Chlorine		Zinc
		Copper

Figure 39 – Nutrient mobility in soil.

In work conducted by Hardie *et al.* 2017 in apples, calcium nitrate was fertigated separately followed by an irrigation event 20 hours later under high and low irrigation treatments. Figure 40 shows the results in timelapse and illustrates the variable nature of soils and the influence irrigation events could have on the distribution of mobile nutrients such as nitrate in the soil profile. Adding nutrients via fertigation should be considered towards the end of the irrigation event to avoid leaching beyond the rootzone and irrigation intervals after fertigation events could impact nutrient distribution within the soil profile.

***Figure 40** is the change in electrical resistivity: time-lapse inversion model demonstrating the change in electrical resistivity from the first reference model to **a** 1 h after fertigation, **b** 20 h after fertigation, **c** 46 h after fertigation and 26 h after irrigation, and **d** 66 h after fertigation and 46 h after irrigation. Dark blue arrows represent the location of the low irrigation treatment emitters, green arrows represent the location of the high irrigation treatment emitters, red arrows indicate the location of the fertigation emitters. Left side (1.0–8.0 m) low irrigation treatment. Right side (8.0–15 m) is the high irrigation treatment.*

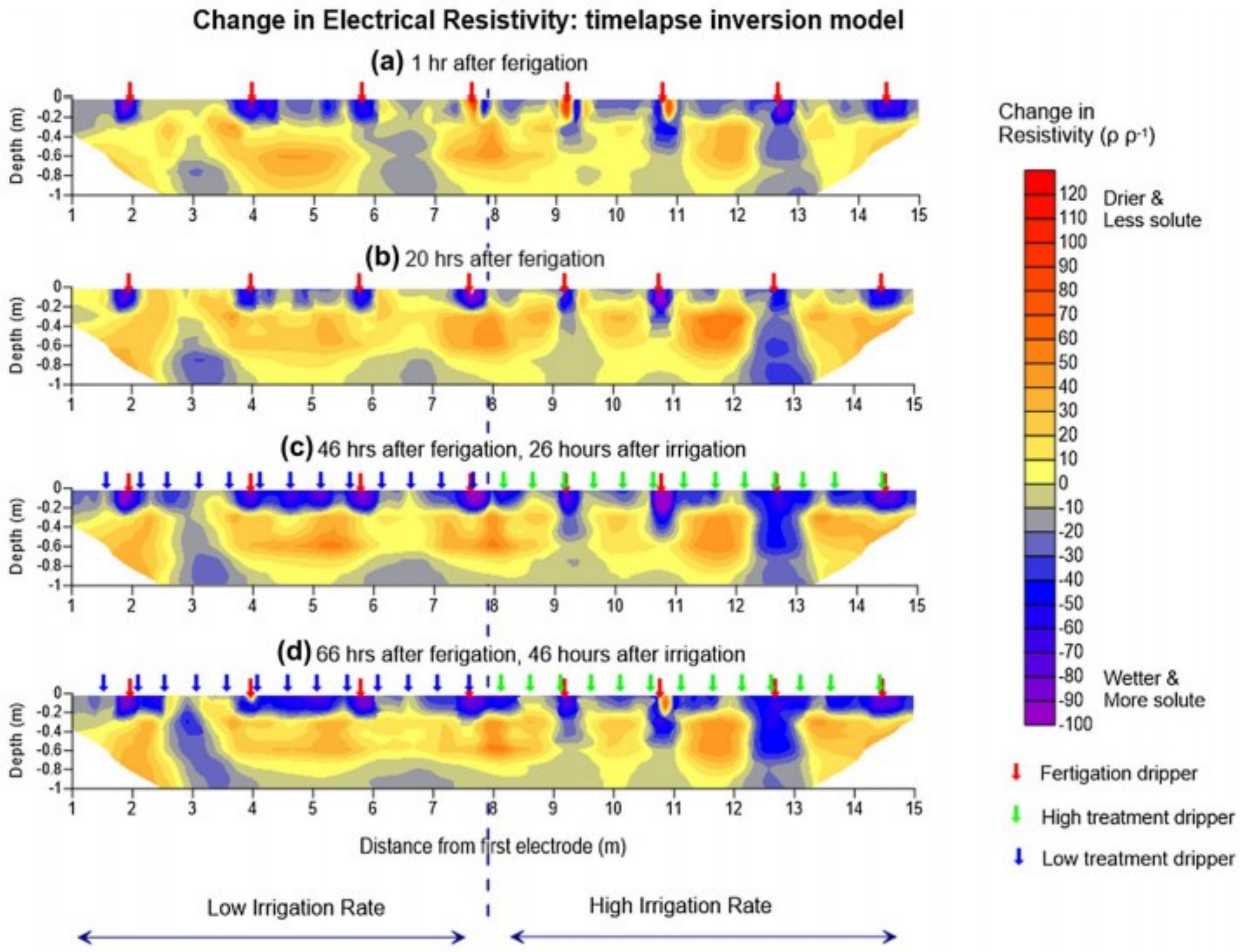


Figure 40 – Change in electrical resistivity: time-lapse inversion model demonstrating the change in electrical resistivity from a fertigation event followed by an irrigation event (Hardie *et al.* 2017).

Low water availability can reduce the amount of nutrients available to the tree as demonstrated by work conducted by Kaneko 2016 on control well-watered and droughted avocado trees (Figure 41).

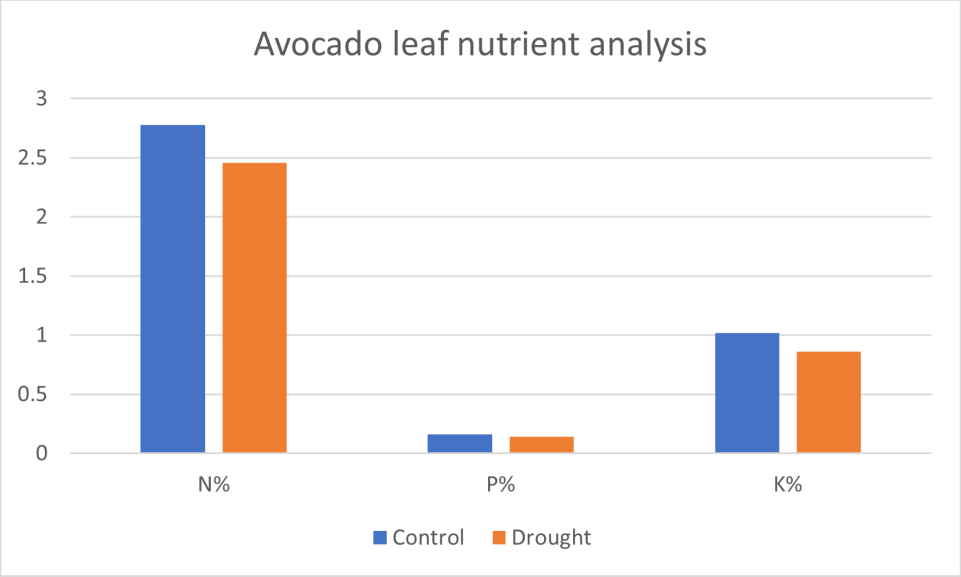


Figure 41 – Avocado leaf nutrient analysis of well-watered versus droughted trees (Kaneko 2016). N – nitrogen, P – phosphorous, K – potassium.

Soil biology is also an important consideration when irrigating orchards. Orchard and Cook 1983 showed that wetting and drying cycles changed microbial activity in soil with six different water potentials (Figure 42). The soils with higher water potential (1, 2, 3) had higher microbial activity overall, indicating the importance of moisture.

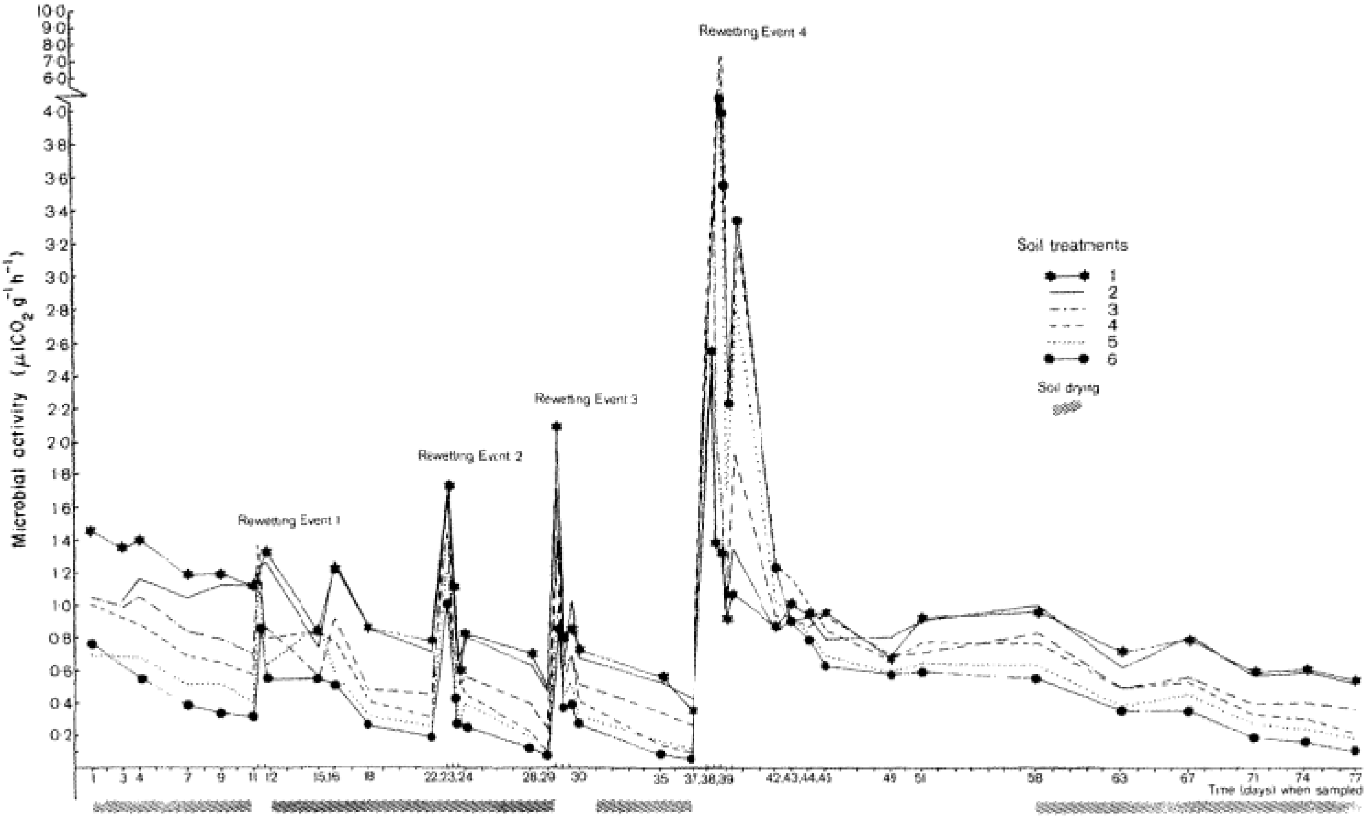


Figure 42 – Changes in microbial activity as soil at six different water potentials are dried and rewetted. Treatments 1,2 and 3 are the wetter soil samples and 4, 5 and 6 are the dryer soil samples (Orchard & Cook 1983).

7.7 Oxygen

Irrigation frequency to balance the tree's access to oxygen in the soil will depend on your soil type, bulk density and soil condition. Ferreyra *et al.* 2010 (Figure 43) demonstrates what happens to the soil oxygen level under different irrigation scheduling in a loamy soil with 50% porosity. As can be seen the high frequency (daily), high volume irrigations keep the soil moisture above field capacity and the air content is around the 17% which Ferreyra *et al.* 2007 indicated was the threshold for avocado root hypoxia. Decreasing the frequency of irrigation and the volume supplied can increase the soil air content as illustrated by the other two irrigation methods. There is no mention of a safe time period for avocado root exposure to low oxygen, however Stolzy *et al.* 1967 indicated that when the oxygen diffusion rate dropped below 0.17ug / cm / min., 44-100% of 'Mexicola' avocado roots were damaged.

Irrigation focuses on meeting tree water requirements to achieve production goals. However, given the soil water-to-air ratio has been highlighted by Gil *et al.* 2008a to have a significant impact on production goals, understanding your soil's field capacity and air content when irrigating provides the opportunity to develop new irrigation strategies that could benefit production.

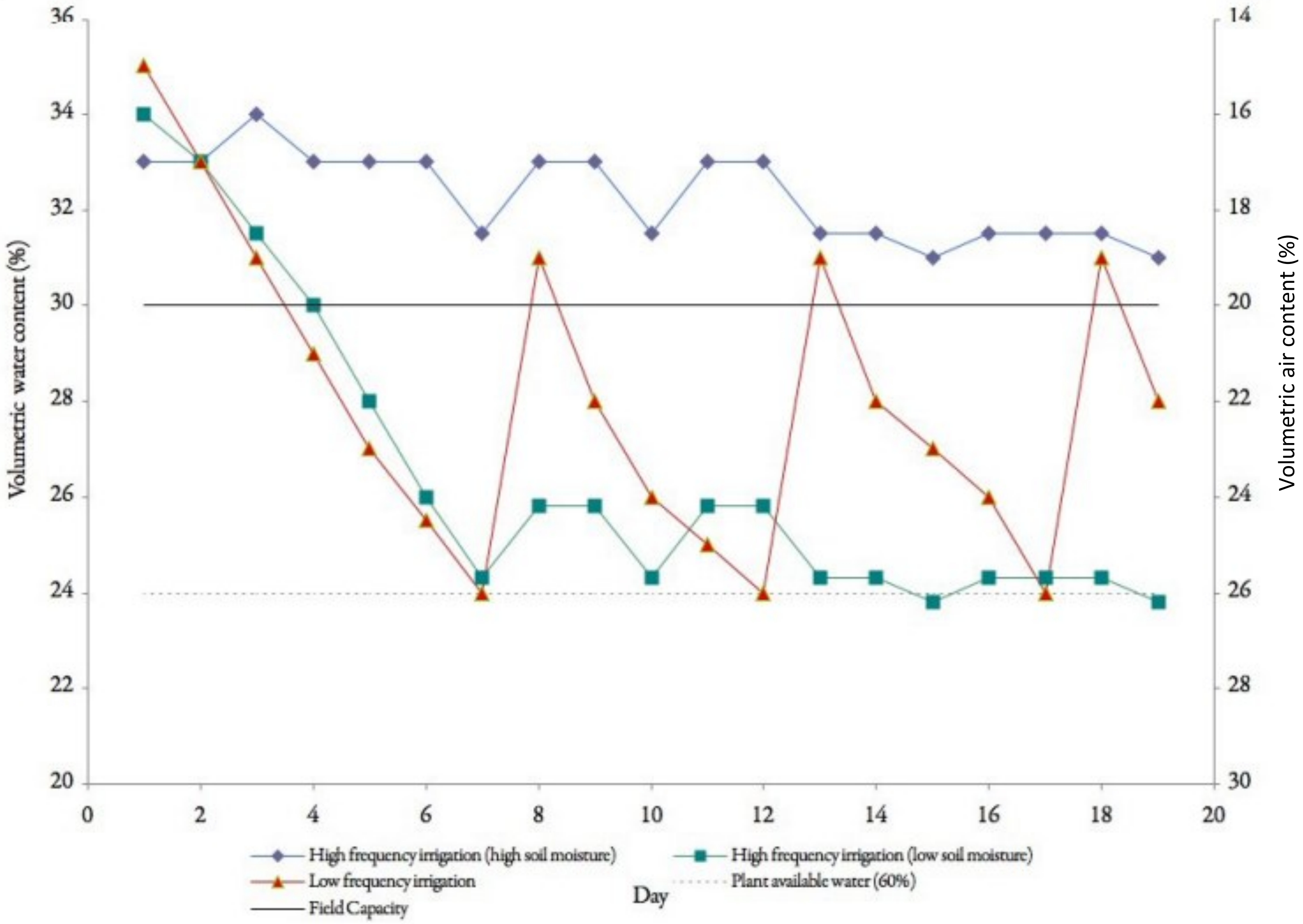


Figure 43 – The influence of high and low irrigation frequencies on soil aeration (Ferreyra *et al.* 2010)

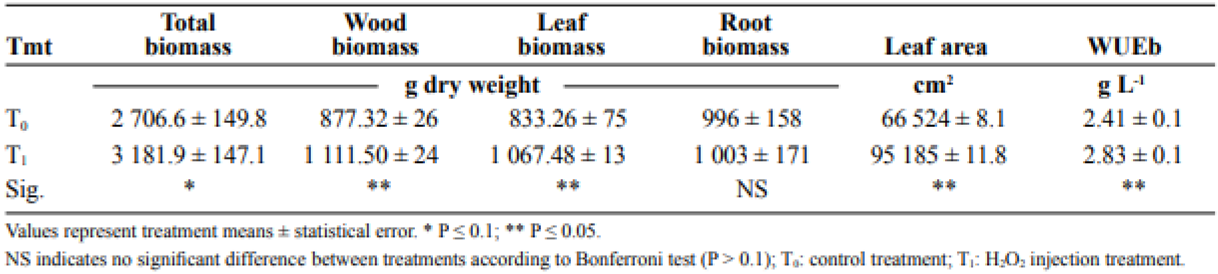
For avocados already growing on heavy soils, oxygation may be worth investigating to improve oxygen levels in the rootzone during irrigation events. Oxygation is defined as irrigating with aerated water using air injection system or hydrogen peroxide generally with subsurface drip.

Central Queensland University researchers (S.P. Bhattarai & D.J. Midmore) have successfully shown improvements in annual crops (growth & production) grown on heavy soil types by increasing oxygen content in irrigation water using a Mazzei air-injector or the Seair Diffusion System (Chen *et al.* 2011). While this research has not been conducted in trees, Zhao *et al.* 2019 showed in grapes that by aerating the irrigation water, new leaves, fine roots and branches were promoted.

Gil *et al.* 2009 also suggested the addition of hydrogen peroxide to irrigation water as another method to increase oxygen levels in the soil profile during irrigation events. Hydrogen peroxide naturally degrades to provide oxygen and water as follows:

$$H_2O_2 + H_2O \longrightarrow 0.5\ O_2 + 2\ H_2O$$

Gil *et al.* 2009 demonstrated that injecting hydrogen peroxide in the irrigation water significantly increased the growth of the avocado trees (Figure 44). While the experiment was done on potted trees it showed promise for improving oxygen levels in air deprived soils.



Tmt	Total biomass	Wood biomass	Leaf biomass	Root biomass	Leaf area	WUEb
	g dry weight				cm^2	g L^{-1}
T_0	2 706.6 ± 149.8	877.32 ± 26	833.26 ± 75	996 ± 158	66 524 ± 8.1	2.41 ± 0.1
T_1	3 181.9 ± 147.1	1 111.50 ± 24	1 067.48 ± 13	1 003 ± 171	95 185 ± 11.8	2.83 ± 0.1
Sig.	*	**	**	NS	**	**

Values represent treatment means ± statistical error. * $P \leq 0.1$; ** $P \leq 0.05$.
NS indicates no significant difference between treatments according to Bonferroni test ($P > 0.1$); T_0: control treatment; T_1: H_2O_2 injection treatment.

Figure 44 – Final biomass, leaf area and water use efficiency (WUEb) of avocado trees treated with Hydrogen peroxide (Gil *et al.* 2009). Both T_0 and T_1 are 'Hass' avocado on 'Mexicola' seeding rootstocks grown in heavy loam clay soil. Both treatments were watered to maintain field capacity T_0 is the control and T_1 was injected with Hydrogen peroxide.

7.8 Salt

Avocado trees are highly sensitive to salt (0.57 ds/m-1 - Mass & Grattan 1999). As irrigation water availability declines, salt can become concentrated forcing growers to irrigate trees with salty water that is detrimental to tree health (chloride burn in leaves) and yield (yield loss above 0.57 ds/m-1 is 63% per ds.m-1 (Oster *et al.* 2007)). Once salt levels in the root zone reach approx. 4 dS.m-1 it has been reported avocado water uptake is restricted (Oster *et al.* 2007). Given that all fertilisers are salts and fertigation delivers directly to the rootzone, the use of fertigation with salty water may exacerbate salinity damage during dry times.

Salt mitigation is a difficult situation for many growers when water availability is low, available water is salty and leaching irrigations are not possible. High rootzone salt levels change the osmotic pressure, causing nutrient imbalances and toxicities reducing tree growth and function.

Water moves from the soil to the plant via osmosis, which is a diffusion of water from a zone containing less salt (low solute concentration) to a zone containing more salt (high solute concentration) along a gradient. When salinity rises in the rootzone, the diffusion gradient changes with the high solute concentration located in the soil rather than the plant; decreasing water potential and making it harder for the plant to extract water (Castro *et al.* 2009).

Solute concentrations will also change in the plant with sodium and chloride causing tissue damage (Mickelbart *et al.* 2007) and potassium (Walker *et. al* 1983, Mickelbart *et al.* 2007) and calcium working to rebalance the osmotic pressure gradient and alleviating plant salinity stress (Alvarez – Acosta *et al.* 2017). Therefore, tree nutrition should be reviewed under saline conditions to ensure availability of potassium and calcium.

Rootstocks have been shown to impart salt tolerance in avocado scion - West Indian rootstock > Guatemalan rootstock > Mexican rootstocks (Mickelbart *et al.* 2007). On a recent visit to California, researcher Dr. Mary Lu Arpaia described the issues that California is facing with limited water supplies that are high in salt. She indicated that salinity tolerance in rootstocks is now a high priority in their rootstock breeding program.

Celis *et al.* 2018 assessed the salt tolerance and growth of thirteen avocado rootstocks. Rootstocks were subjected to irrigation with non-saline water (control, EC= 0.65dS·m– 1) and saline water (EC = 1.5 dS·m–1). Rootstocks that showed the best results included the commercially available Dusa^{TM}; Westfalia selections R0.05 and R0.18, as well as University of California Riverside selection PP40 as illustrated by survival rate (Figure 45), leaf burn (Figure 46) and yield (Figure 47). While these selections showed the best results in this study, the conclusions reported by the researchers suggest that none of the selections tested were particularly promising for high salinity levels. Also it is interesting to note that the control salt level is above the reported threshold for avocados.

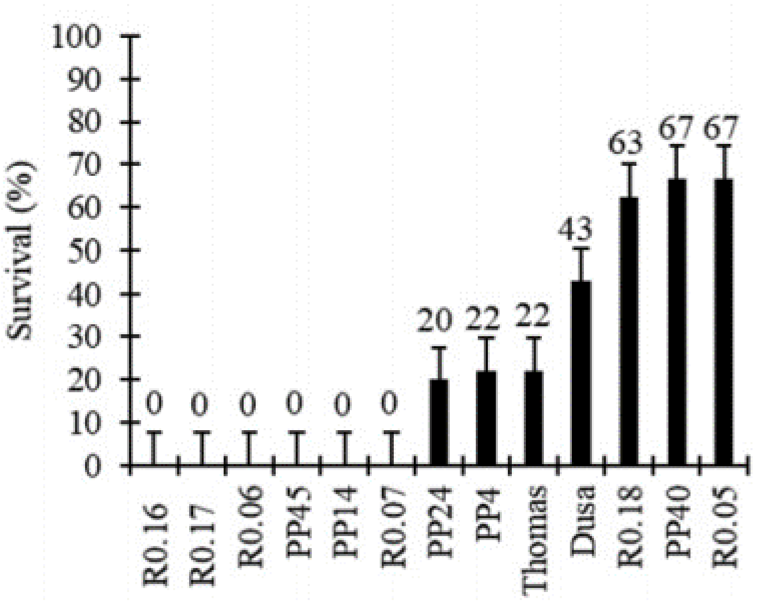


Figure 45 – Avocado survival percentage by rootstock in saline treatment in 2015 (Celis *et al.* 2018). After being irrigated with saline water for 20 months, only 7 varieties survived.

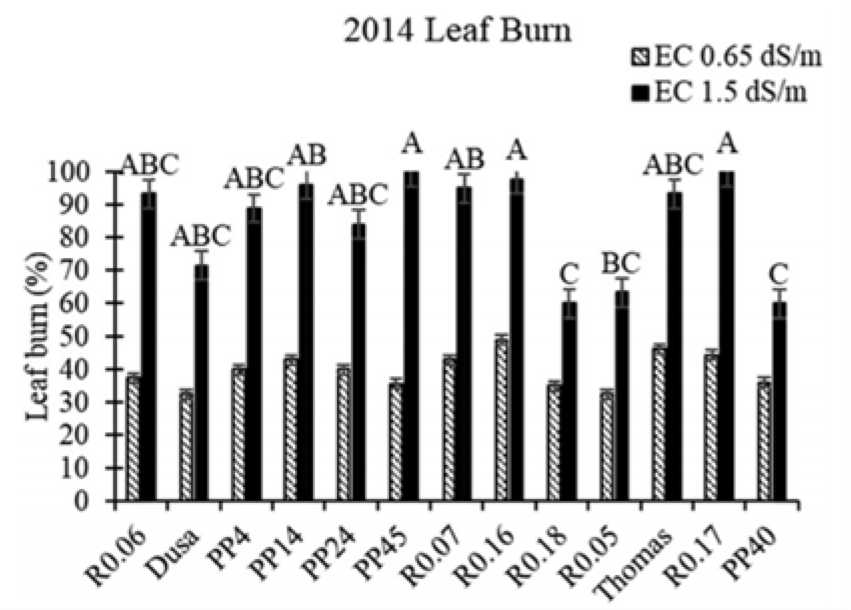


Figure 46 – Leaf burn percentage for each rootstock in in rows irrigated with an electrical conductivity (EC) of 0.65 ds/m and 1.5 dS/m in 2014 (Celis *et al.* 2018).

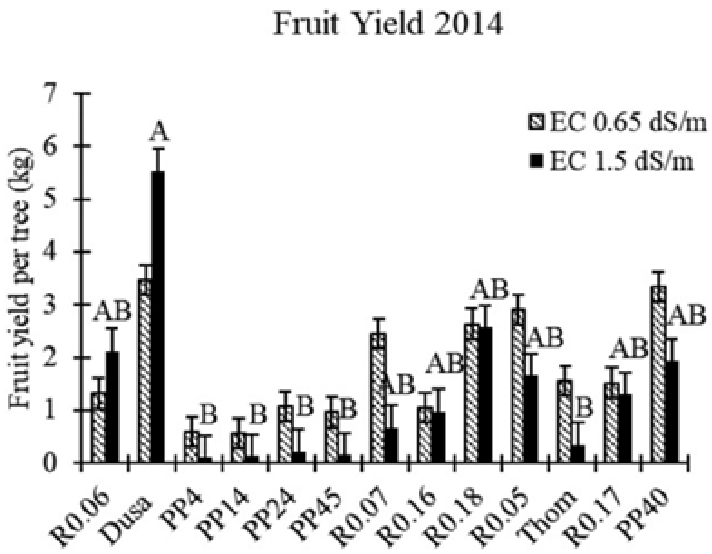


Figure 47 – Average fruit yield per tree for each rootstock irrigated with an electrical conductivity (EC) of 0.65 ds/m and 1.5 dS/m in 2014 (Celis *et al*. 2018).

In work conducted by Castro *et al.* 2009, the rootstock 'Nabal'(Guatemalan) restricted chloride transport to old and new leaves, suggesting a level of salt tolerance. Zutano accumulated more chloride in older leaves than new leaves but recorded a high level of calcium in the roots and produced shoots faster than any other rootstock treated with high saline conditions.

While rootstock selection is a long-term solution to managing salinity, there may be some developmental or commercially available products that could assist avocado trees tolerate saline irrigation water for short periods. Bonomelli *et al.* 2018 suggested that the addition of seaweed (in this study a brown seaweed *Ascophyllum nodosum*) may moderate salt stress in the tree and allow for continued growth in comparison to a solely saline situation. This is illustrated in Figure 48 comparing TS which is saline water (9 mM NaCl) and TS+ 1.5SW which is saline water (9 mM NaCl) and 1.5mL seaweed extract and TS+2.25SW which is saline water (9 mM NaCl) and 2.25mL seaweed extract. There are many different seaweed products made from different seaweed varieties and concentrations that should be considered before application.

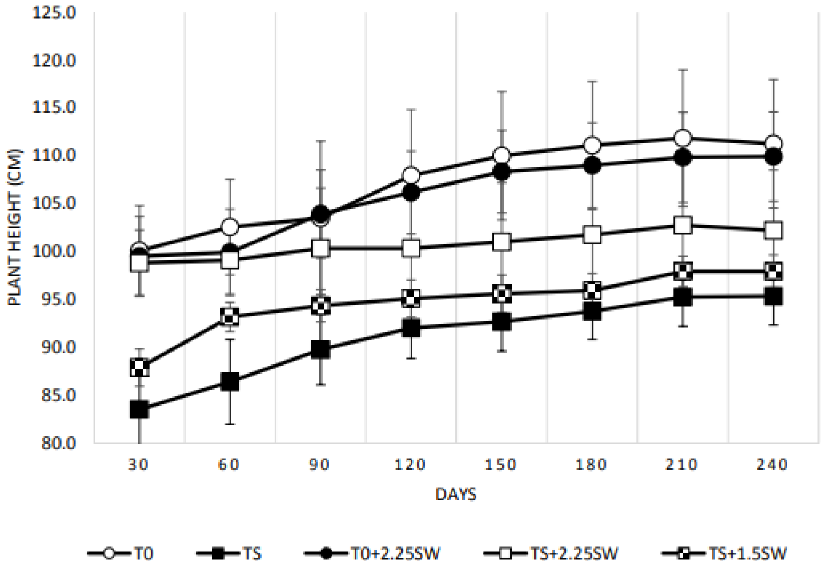


Figure 48 – Changes in plant height in 2 year old 'Hass' avocado plants grown in pots subjected to salinity and seaweed treatments (Bonomelli *et al.* 2018). T0 – distilled water, TS – saline water (9 mM NaCl), T0 +2.25SW – distilled water + 2.25 mL seaweed, TS + 2.25SW – saline water (9 mM NaCl) + 2.25 mL seaweed, TS + 1.5SW - saline water (9 mM NaCl) + 1.5 mL seaweed.

Barra *et al.* 2016 suggested in their study that there are strains of plant growth-promoting bacteria that are tolerant to high salinity levels. These bacteria produce indole acetic acid (IAA) promoting root growth and 1-aminocyclopropane-1-carboxylic acid (ACCD) suppressing the ethylene precursor (1-aminocyclopropane-1-carboxylic acid - ACC) that generates a stress signal in the plant and inhibits root growth. Barra *et al.* 2016 reported that the *Enterobacter* sp., *Serratia* sp. and *Achromobacter* sp. mix produced the best results in reducing salt stress in the avocado seedling trees by increasing root fresh weight and length, improving the root surface area for water and nutrient uptake and continued growth and function of the tree.

Silicon has been reported in several field crops to improve plant growth, function and yield under high salt conditions (Ali *et al.* 2012). More consideration is required for avocados with no available work on the status of Silicon accumulation by avocados or benefits in tolerating saline conditions.

7.9 Phytophthora Root Rot

Root rot caused by *Phytophthora cinnamomi* presents the same symptoms as water stress (reduced growth and wilting). Research conducted by Sterne *et al.* 1978 confirmed reduced water use efficiency in trees infected with Phytophthora, reporting decreased transpiration in comparison to healthy trees. Given *Phytophthora cinnamomi* requires free water for dispersal, irrigating can facilitate the spread of this pathogen within the orchard.

Phytophthora is an aerobic organism and like avocado roots requires oxygen and does not favour water-logged soils (Dann *et al.* 2013). Figure 49 illustrates the Phytophthora life cycle and the range of soil water potentials in which the different stages can survive (0 kPa – saturated, -1000kPa - dry). The speed of the lifecycle and thus infection is related to temperature and oxygen as well as soil moisture for transport and can occur within 24 – 72 hours under favourable environmental conditions.

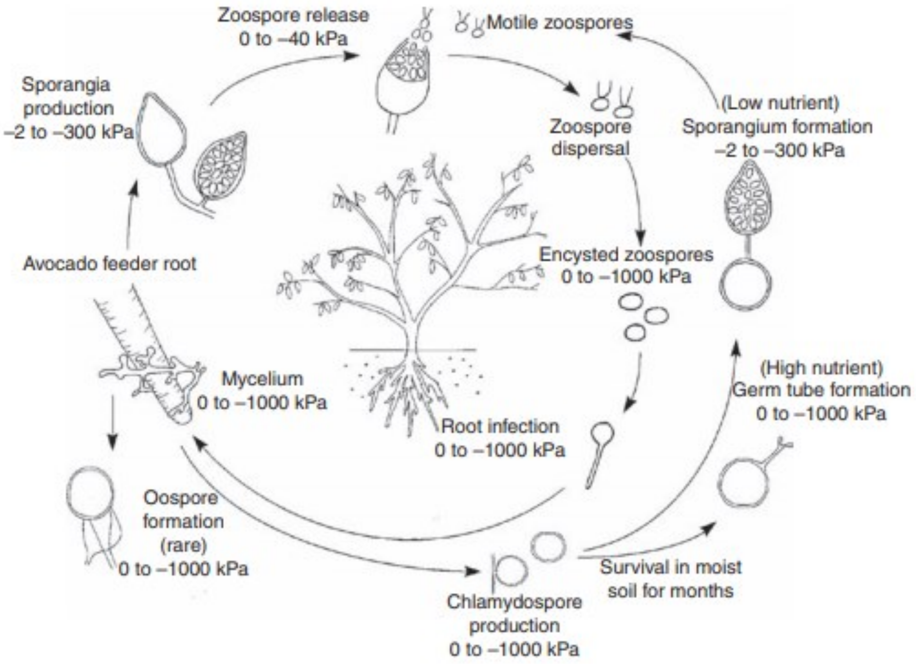


Figure 49 – Soil water potentials for the lifecycle of *Phytophthora cinnamomi* (Dann *et al.* 2013).

Reeksting *et al.* 2014 suggested that the effects of flooding and *Phytophthora cinnamomi* infection caused more damage to avocado trees than flooding or infection separately (Figure 50); including overall reduced photosynthesis, transpiration and stomatal conductance despite differences between rootstocks with tolerance to *Phytophthora cinnamomi* (Figure 51).

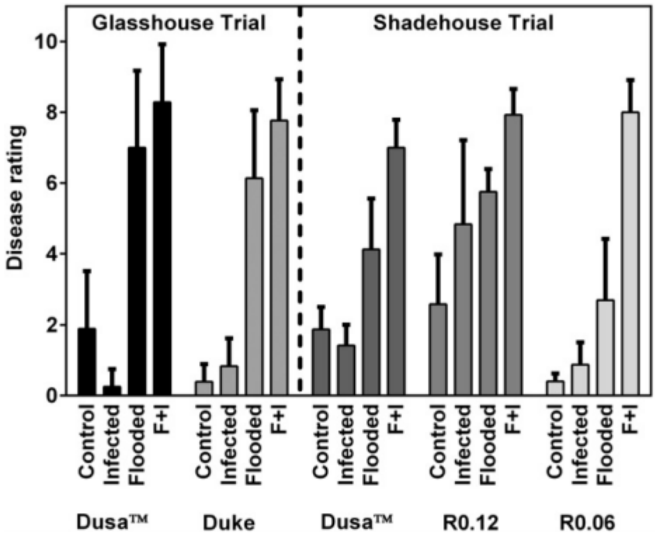


Figure 50 — Plant disease rating of two trials evaluating Dusa^{TM}, Duke 7, R0.12 and R0.06 rootstocks subjected to *Phytophthora cinnamomi* infection, flooding and a combinational treatment (Reeksting *et al.* 2014). Rating ranges from 0 (healthy) to 10 (dead).

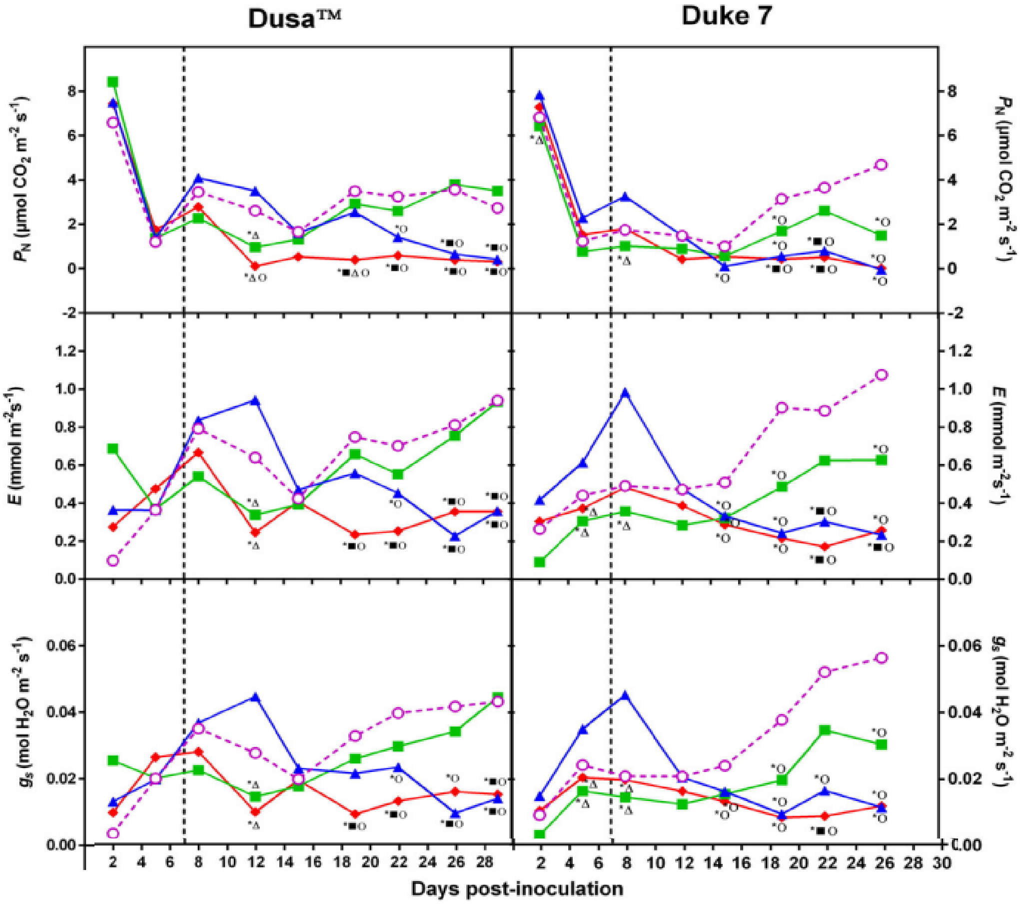


Figure 51 — Effects of *Phytophthora cinnamomi* and flooding on net photosynthesis (PN), transpiration (E), stomatal conductance (gs) for Dusa^{TM} and Duke 7 avocado rootstocks (Reeksting *et al.* 2014). Infected and flooded (diamonds), infected (squares), flooded (triangles), control (circles). Flooding began at day 7 as indicated by the dotted line.

The damage caused to roots by flooding, Phytopthora root rot infection and a combinational effect was demonstrated in Duke 7 rootstock (Figure 52) and Reeksting *et al.* 2014 strongly recommended avoiding flooding in avocado orchards to maintain tree health and productivity. Faber *et al.* 2003 reported that the presence of mulch improved aeration for the avocado shallow root system and reduced Phytophthora root rot incidence in roots growing into mulch.

As noted in section 6.8 on salt, different rootstocks have shown tolerance to *Phytophthora cinnamomi* infection. Reeksting *et al.* 2014 reported that ‘Dusa$^{\text{TM}}$’ and R0.06 had a greater tolerance than Duke 7 rootstock, yet ‘Duke 7’ and ‘Barr Duke’ are reported to have moderate tolerance (Phillips *et al.* 1991). Smith *et al.* 2011 found ‘Reed’ to be highly susceptible, and ‘SHSR-02’, ‘SHSR-04’, ‘Dusa$^{\text{TM}}$’ and ungrafted ‘Hass’ to show tolerance to infection.

Research relating to rootstocks, irrigation methods, water volumes or frequencies and the response of *Phytophthora cinnamomi* in avocados could be beneficial to the management of Phytophthora root rot in Australian avocado orchards.

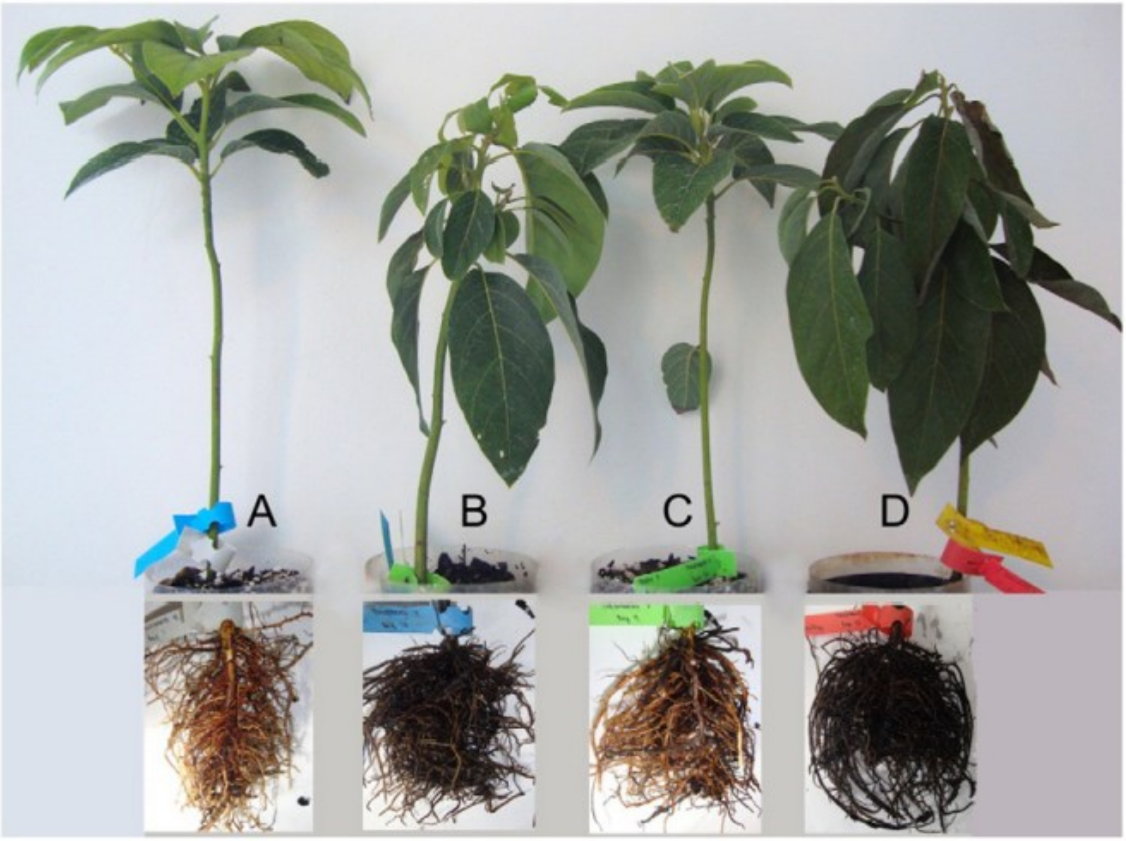


Figure 52 — Effects of *Phytophthora cinnamomi* and flooding on Duke 7 avocado plants (Reeksting *et al.* 2014). Healthy control plants (A), flooded plants (B), infected plants (C), and flooded and infected plants (D).

7.10 Alternate bearing

Silber *et al.* 2019 reported that treatments with no water stress or excessive watering did not show an alternate bearing cycle whereas water stress treatments regardless of phenological timing or time period stressed demonstrated the on and off crops associated with alternate bearing.

Moreno-Ortega *et al.* 2019 measured the impacts of irrigation volume on alternate bearing and illustrated in their study that reduced watering reduced the impact of the alternate bearing cycle and over watering increased the impact.

Yet Holzapfel *et al.* 2017 reported the opposite with an increasing trend for alternate bearing as irrigation was reduced and a decreasing trend with increased water application and suggested that water scheduling should be maintained even in off -cropping years.

7.11 Mulching

Mulching materials have been used to boost the avocados natural mulching system, retaining moisture at the top of the soil profile and relieving stress experienced under low water availability (Figure 53 - Faber *et al.* 2003).

Fruit productivity was shown to significantly increase with the addition of mulch attributed to prolonged and extensive root growth (Moore-Gordon *et al.* 1997) and perhaps reduced environmental stress caused by increased water retention. Faber *et al.* 2003 also recorded an increase root length attributed to the addition of mulch.

The addition of mulch has proven useful in irrigation scheduling with retention of moisture in the root zone allowing for decreased frequency of irrigation, however caution should be taken when selecting mulching materials particularly regarding moisture holding capacity and mulching material particle size.

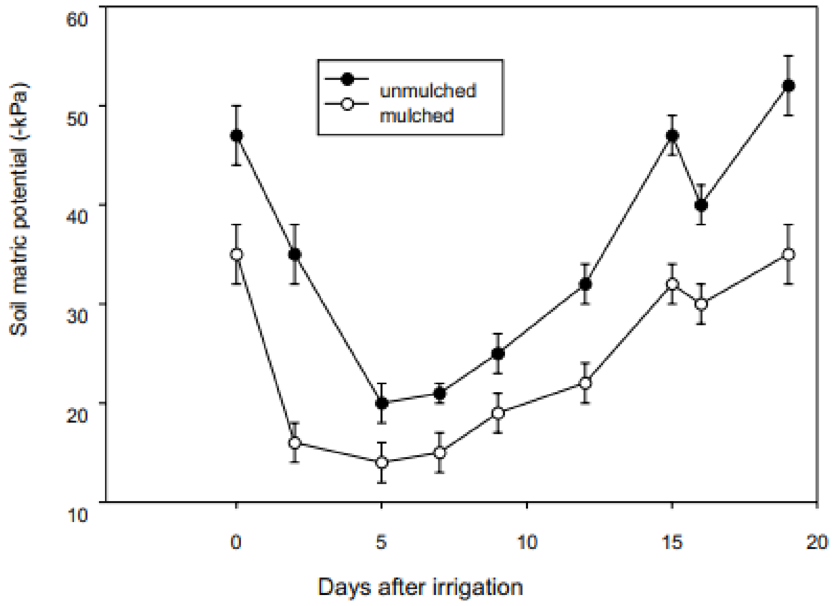


Figure 53 – Soil moisture tension (-kPa) for avocado trees under mulch versus no mulch treatments (Faber *et al.* 2003).

8. Water productivity

To ensure orchard productivity and environmental sustainability, optimal irrigation practices are key. Yet in Australia, it is becoming a battle between water availability and water use efficiency in the orchard; where to use available water to get the best results?

Water use efficiency is not just how much water is used in the orchard annually (e.g. Spain - 7000 m3 / ha / season mature avocado grove (Moreno-Ortega *et al.* 2019) and Chile - 8000-9000 m3 /ha /season (Ferreyra & Selles 2012)) but takes into consideration the volume of fruit produced.

Holzapfel *et al.* 2017 determined the relation between water and productivity is positive (Figure 54). However, water is a diminishing resource and avocado producers can make water allocation decisions and potential water savings by reviewing yield, profit and orchard water use to highlight best performing blocks, repeatability of performance and underperforming blocks.

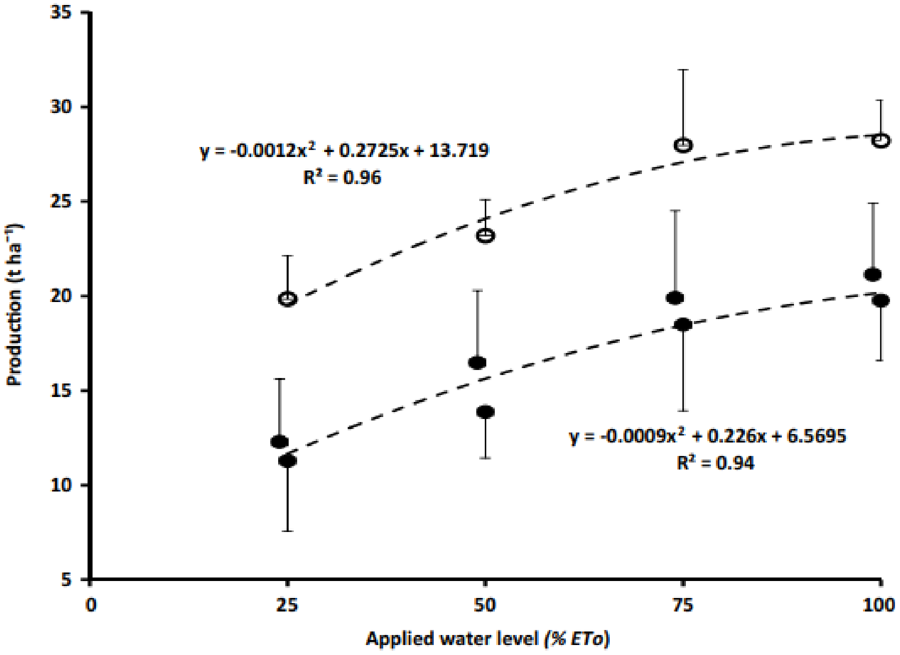
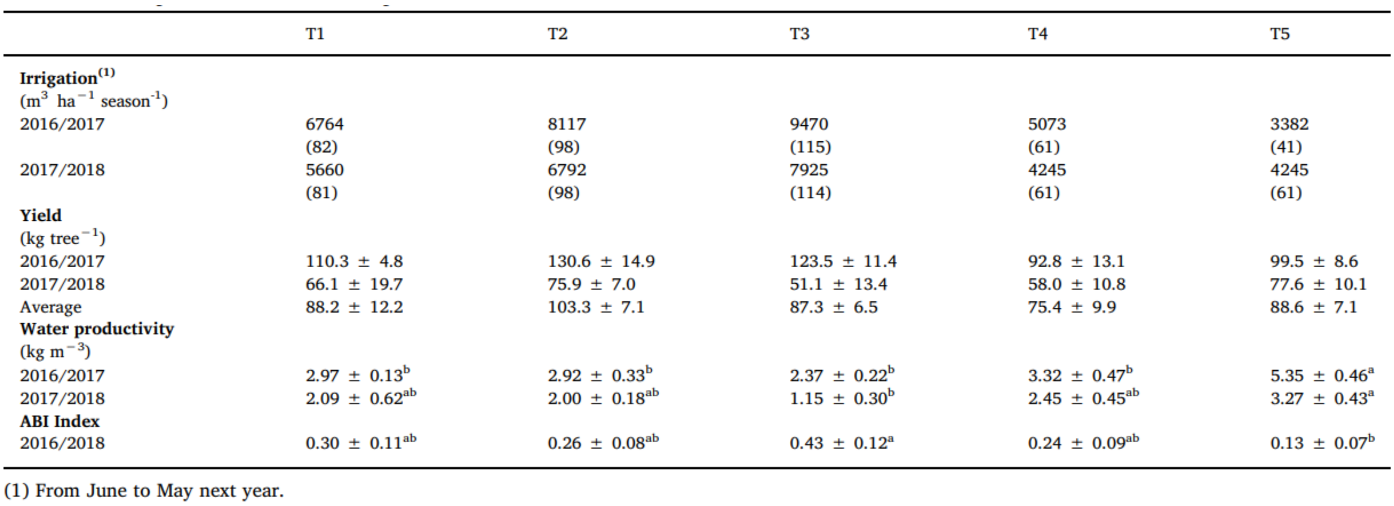


Figure 54 – Production (t/ha) in response to applied water levels (25, 50, 75, 100% ET_0) as calculated with a Class A evaporation pan for 2005/06 (upper open circles) and 2006/07 (lower closed circles) (Holzapfel *et al.* 2017).

Moreno-Ortega *et al.* 2019 reported water productivity as kg of fruit produced per cubic metre of water used under 5 different irrigation treatments (Figure 55). T2 was considered to supply water to meet tree water requirements at approximately 8 ML / ha in 2016/17, resulting in 2.92 kg of fruit per m^3 water. As can be seen by this study over watering (T3) resulted in a lower water productivity (2.37 kg/m^3) and watering significantly under the tree water requirements (T5) resulted in a high water productivity (5.35 kg/m^3).



	T1	T2	T3	T4	T5
Irrigation$^{(1)}$ (m^{3} ha^{-1} season^{-1})					
2016/2017	6764 (82)	8117 (98)	9470 (115)	5073 (61)	3382 (41)
2017/2018	5660 (81)	6792 (98)	7925 (114)	4245 (61)	4245 (61)
Yield (kg tree^{-1})					
2016/2017	110.3 ± 4.8	130.6 ± 14.9	123.5 ± 11.4	92.8 ± 13.1	99.5 ± 8.6
2017/2018	66.1 ± 19.7	75.9 ± 7.0	51.1 ± 13.4	58.0 ± 10.8	77.6 ± 10.1
Average	88.2 ± 12.2	103.3 ± 7.1	87.3 ± 6.5	75.4 ± 9.9	88.6 ± 7.1
Water productivity (kg m^{-3})					
2016/2017	2.97 ± 0.13^{b}	2.92 ± 0.33^{b}	2.37 ± 0.22^{b}	3.32 ± 0.47^{b}	5.35 ± 0.46^{a}
2017/2018	2.09 ± 0.62^{ab}	2.00 ± 0.18^{ab}	1.15 ± 0.30^{b}	2.45 ± 0.45^{ab}	3.27 ± 0.43^{a}
ABI Index					
2016/2018	0.30 ± 0.11^{ab}	0.26 ± 0.08^{ab}	0.43 ± 0.12^{a}	0.24 ± 0.09^{ab}	0.13 ± 0.07^{b}

(1) From June to May next year.

Figure 55 – Water supplied by irrigation, yield, water productivity for the last two experimental seasons in the five irrigation treatments (T1-T5). Figures in brackets under each irrigation volume indicate the % meeting tree water requirements as calculated by FAO paper 56 (Moreno-Ortega *et al.* 2019). *Note - Trees - 178 /ha.*

Calculating water productivity starts with good irrigation data that can be broken down into blocks / phenological timing and harvest data per block. While T5 showed a high water productivity, it exhibited poor tree health and fruit drop throughout the study and therefore determining commercial water productivity for individual orchards and at an industry level could assist growers in improving orchard water use efficiency and long-term sustainability.

Other industries have collected data on water productivity (below) and a new study run by the Food Agility CRC in Manjimup, Western Australian is starting to collect data for avocados.

- ***On-farm Water Demand*** - https://www.foodagility.com/projects/on-farm-water-demand
- ***Winegrapes*** – Murray Valley & Riverina Water Use Efficiency study 2011/12 –

  http://www.mvwi.com.au/items/444/Murray%20Valley%20&%20Riverina%20WUE%20study%202011-12%20Final%20Report.pdf
- ***Winegrapes*** – Murray Valley & Riverina Water Use Efficiency study 2012/13—

  http://www.mvwi.com.au/items/577/MVWI%20%20Riverina%20WUE%20Report%202012-13.pdf

9. Monitoring

Monitoring climatic conditions, soil moisture and tree conditions ensures water is availability when the tree needs it and that this valuable resource is not wasted by watering beyond the rootzone.

9.1 Evapotranspiration

Monitoring climatic conditions to make decisions on tree water requirements is widely used in the form of crop evapotranspiration (ET_c) calculations. This method uses weather data to calculate reference evapotranspiration (ET_0) using a standardised vegetated surface (i.e grass) and crop co-efficient (Kc) which relates to the crop of interest e.g. avocado.

$$ET_c = ET_0 \text{ x } K_c$$

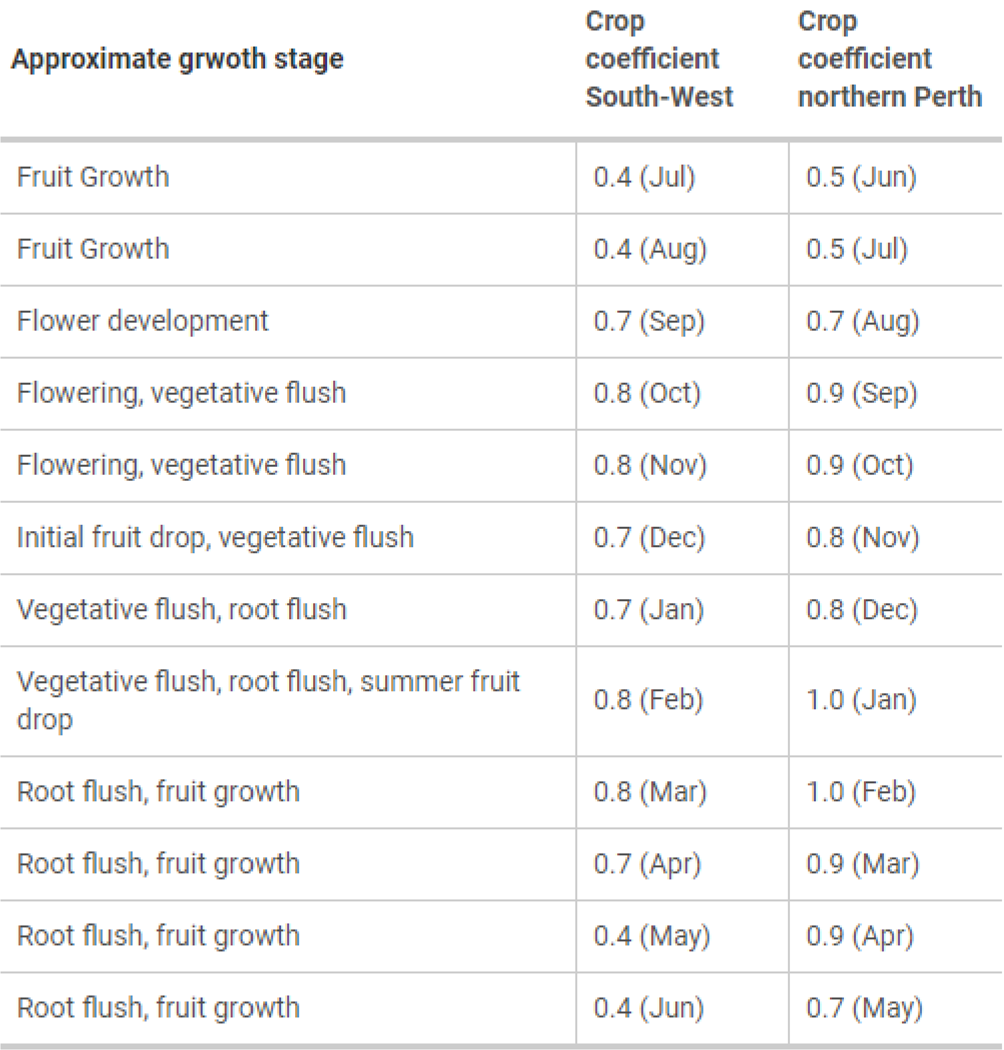
Evapotranspiration is a combination of water evaporation from the soil / plant surface and water transpired by the plant (Burman *et al.* 1994). Reference evapotranspiration is generally calculated using the widely accepted Food and Agricultural Organisation of the United Nation (FAO) Penman-Monteith equation found in the FAO Irrigation and Drainage Paper 56 (Allen *et al.* 1998). There is also reference to another method by the American Society of Civil Engineers – Environmental and Water Resources Institute (ASCE-EWRI 2005).

The Australian Bureau of Meteorology uses the Penman-Monteith equation to calculate the ET_0 figures reported on the BoM's website (www.bom.gov.au) (Webb 2010). Up until 2010 mean daily evaporation figures were reported using pan evaporation. BoM used a Class "A" evaporation pan to measure daily evaporation (mm) from a circular water pan (of known surface area and volume) for a 24 hour period to 9am each morning with a physical measurement. This data can be used to calculate ET_0 data though is considered less reliable than data calculated with the Penman-Monteith equation (Ladson 2008), with readings approximately 20% higher than calculated reference evapotranspiration (Webb 2010) and hence implied higher crop water requirements. Users of long-term BoM data should be cautious of the difference in data before and after 2010 when examining historical crop water requirement data. To access ET_0 data from the Bureau of Meteorology go to http://www.bom.gov.au/watl/eto/

Crop coefficients (Kc) are determined experimentally and take into consideration changes in crop phenology and water requirements. The Western Australian Department of Primary Industries and Regional Development recommend Kc for avocados grown in the South West and northern Perth based on monthly growth stage in Figure 56 (https://www.agric.wa.gov.au/water-management/growing-avocados-–-annual-water-requirements)

In Spain Kc figures based on phenological stages are 0.6 for vegetative stage, 0.85 for flowering, 0.8 flowering / fruit set and 0.75 for fruit growth (Moreno – Ortega *et al.* 2019), while Carr 2013 reported that Kc for mature avocado trees was between 0.4-0.6.

Kiggundu *et al.* 2012 demonstrated in their study that by using ET_0 (Penman-Monteith) and Kc figures when watering young trees they were able make water savings of 93% and 87% savings when using soil moisture monitoring (tensiometers) in comparison to set calendar irrigation scheduling.



Approximate grwoth stage	Crop coefficient South-West	Crop coefficient northern Perth
Fruit Growth	0.4 (Jul)	0.5 (Jun)
Fruit Growth	0.4 (Aug)	0.5 (Jul)
Flower development	0.7 (Sep)	0.7 (Aug)
Flowering, vegetative flush	0.8 (Oct)	0.9 (Sep)
Flowering, vegetative flush	0.8 (Nov)	0.9 (Oct)
Initial fruit drop, vegetative flush	0.7 (Dec)	0.8 (Nov)
Vegetative flush, root flush	0.7 (Jan)	0.8 (Dec)
Vegetative flush, root flush, summer fruit drop	0.8 (Feb)	1.0 (Jan)
Root flush, fruit growth	0.8 (Mar)	1.0 (Feb)
Root flush, fruit growth	0.7 (Apr)	0.9 (Mar)
Root flush, fruit growth	0.4 (May)	0.9 (Apr)
Root flush, fruit growth	0.4 (Jun)	0.7 (May)

Figure 56 - Recommended irrigation crop coefficients (Kc) for avocado production in the South-West and northern Perth in Western Australia based on month and growth stage (https://www.agric.wa.gov.au/water-management/growing-avocados-–-annual-water-requirements)

9.2 Pan evaporation & Vapour pressure deficit (VPD)

In a study examining irrigation frequency, Silber *et al.* 2011 showed that tree water use followed both pan evaporation (Figure 57) and VPD (Figure 58) patterns, though reported under different timelines. The pan evaporation data is reported in weeks and the VPD data is reported in hours, showing water use figures of between approximately 40-110L/tree/day and a maximum of 10L/tree/hr respectively. While pan evaporation and VPD both have been suggested as useful tools for gauging tree water requirements, they do not record the same information (different unit of measure) when reported on the same timeline as seen in Figure 59 (Silber *et al.* 2012).

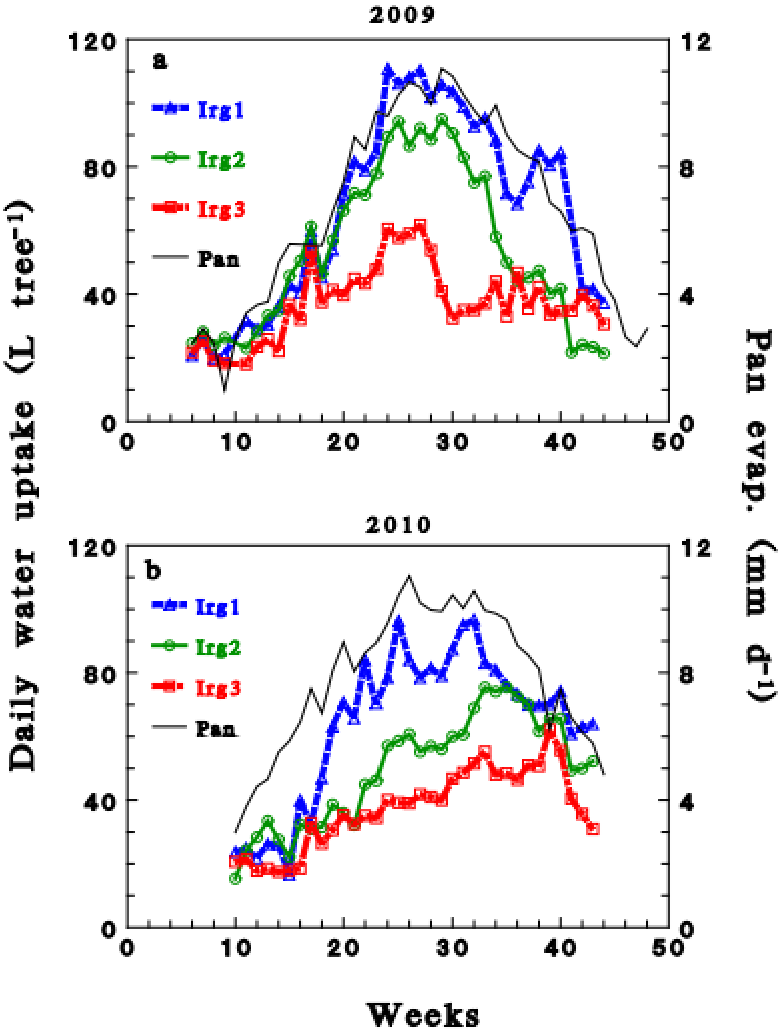


Figure 57 – Using pan evaporation (Class A) to estimate tree water use (Silber *et al.* 2011). Irg1 – pulse irrigation (15 min every 30 min) throughout the day and terminated at 17:00; Irg2 – one daily irrigation event terminated at 9:00; Irg3 - one irrigation event every two days terminated at 17:00 on the first day.

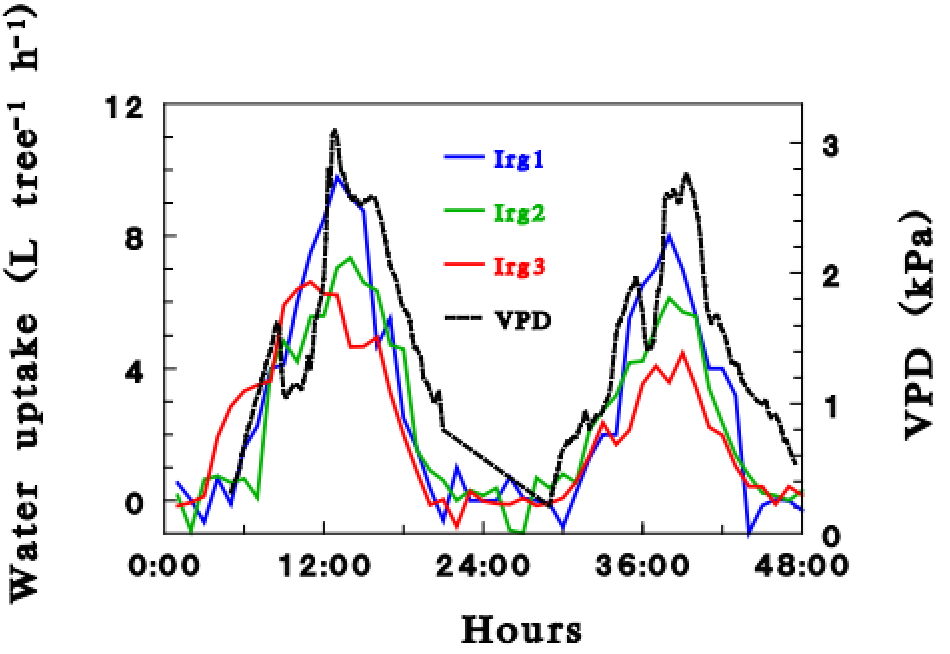


Figure 58 – Water uptake (L / tree / hr) during two representative irrigation events (Silber *et al.* 2011). Total daily water amount was 196 L / tree. Irg1 – pulse irrigation (15 min every 30 min) throughout the day and terminated at 17:00; Irg2 – one daily irrigation event terminated at 9:00; Irg3 - one irrigation event every two days terminated at 17:00 on the first day.

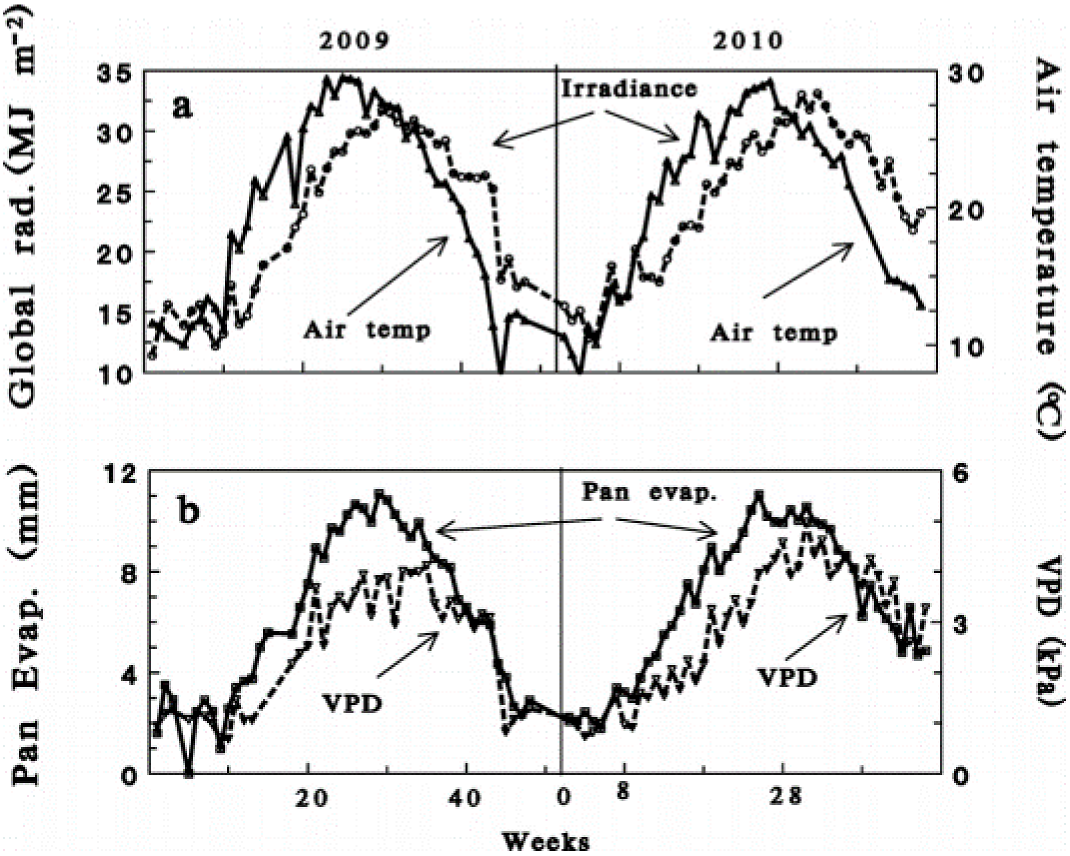


Figure 59 – Measurements of pan evaporation and VPD under the same environmental conditions in 2009 and 2010 (Silber *et al.* 2012).

Silber *et al.* 2013 showed that other environmental factors such as light affect how the tree requires water and may be a consideration for monitoring (Figure 60). Water uptake of the trees under pulse drip irrigation (Irg1 - 18 minutes every 30 minutes from 4am to 7pm) closely followed the irradiance measurements until the middle of the day and then remained high as the VPD increased in the afternoon. Irg2 had separate peaks for both irriadiance and VPD and Irg3 only responded to VPD. Out of interest the daily water uptake for irrigation treatments 1, 2 (one irrigation event daily between 1am and 9am) and 3 (one irrigation event every 2 days from 4am-8pm) were 93L, 52L and 44L per tree / day respectively.

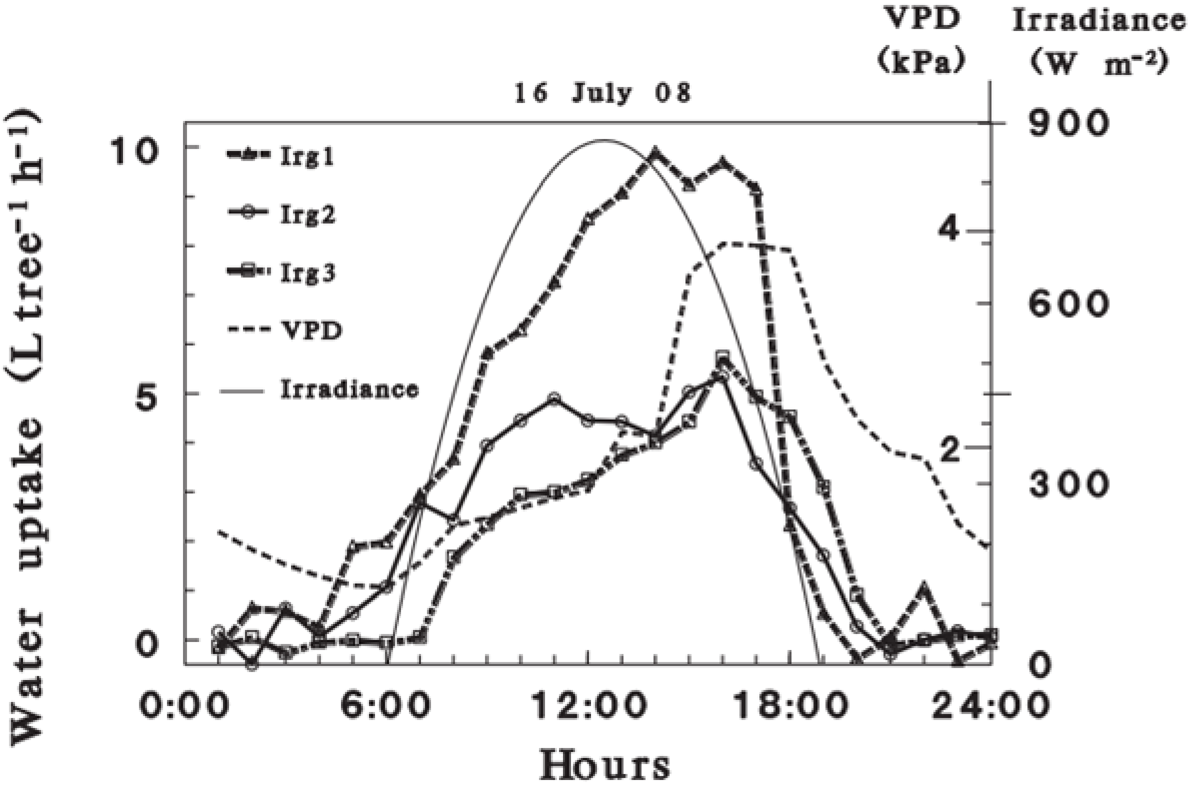


Figure 60 – Relationship of irradiance and VPD to plant water uptake during one representative irrigation event for three irrigation treatments (Silber *et al.* 2013). Total daily water amount was 128L per tree. Irg1 – pulse irrigation (18 min every 30 min) throughout the day starting at 4:00 and terminating at 19:00; Irg2 – one daily irrigation event starting at 01:00 and terminating at 09:00; Irg3 – one irrigation event every two days starting at 04:00 and terminating at 20:00.

Recent studies (Gossiard *et al.* 2020, Yuan *et al.* 2019) have indicated that VPD has increased globally over the past decades and is impacting plant physiological functions to the point of death (Figure 61 - McDowell *et al.* 2008). These studies have highlighted VPD as an important measure for future production and indicate a better working knowledge on the way VPD specifically affects avocado physiology would be beneficial for optimal production in changing climatic conditions.

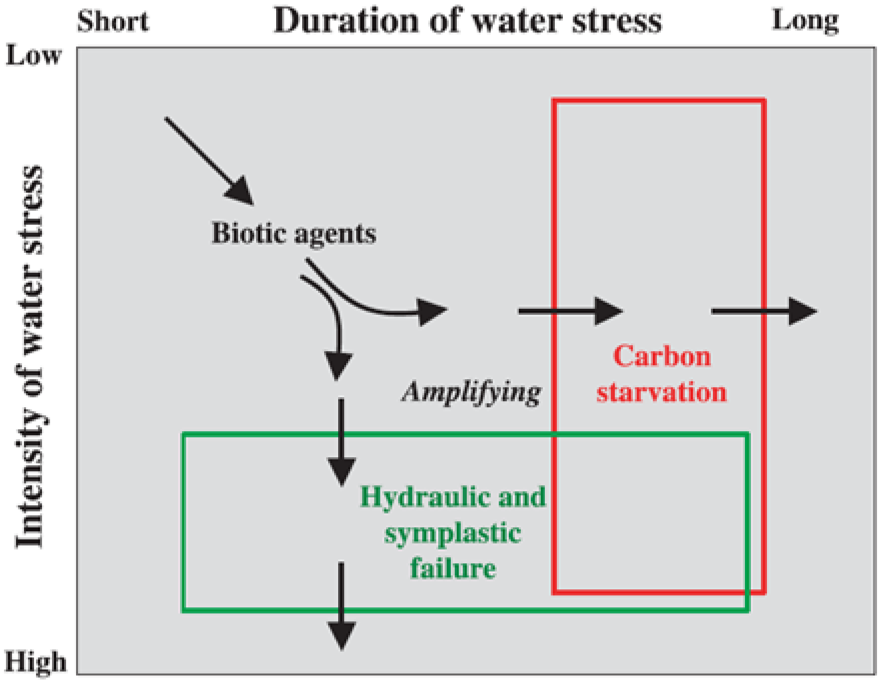


Figure 61 – Three hypothesised mechanisms underlying plant mortality from water stress (McDowell *et al.* 2008). Carbon starvation is hypothesised to occur when drought duration is long enough to curtail photosynthesis longer than the equivalent storage of carbon reserves for maintenance of metabolism. Hydraulic failure is hypothesised to occur if drought intensity is sufficient to push a plant past its threshold for irreversible desiccation before carbon starvation can occur. Biotic agents, such as insects and pathogens, can amplify or be amplified by both carbon starvation and hydraulic failure.

9.3 Trunk measurements

Silber *et al.* 2011 suggested that trunk diameter was an efficient and easy method of determining vegetative status of trees, with changes in irrigation frequency (Figure 62), root volume and stress levels having a detrimental impact on trunk growth.

Dendrometers provide information on the expansion and shrinkage of the trunk, fruit or other organs. They have been investigated in several horticultural tree crops for scheduling irrigation (Silber *et al.* 2013). The two considerations for irrigation scheduling according to Silber *et al*. 2013 are 1. Daily trunk growth rate (mm/day) and 2. Maximum daily variation in trunk diameter (mm).

Irrigation scheduling (timing, duration, amount) has been shown to affect the trunk diameter variation (Figure 63) (Silber *et al.* 2012). Irrigation treatments in a study conducted in 2013 with trees planted in a lysimeter showed that the treatment with the highest water stress (Irg3) showed significant trunk shrinkages under low water and increasing VPD (Silber *et al.* 2013).

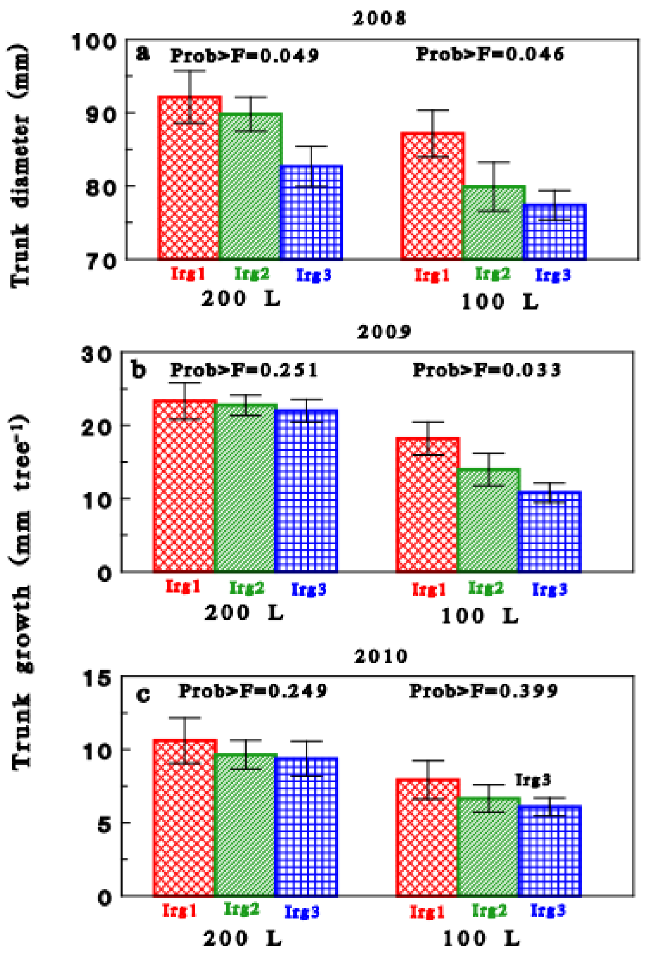


Figure 62 – Effect of irrigation treatments and container volume on (a) trunk diameter at the end of 2008; (b) trunk growth during 2009; an (c) trunk growth during 2010 (Silber *et al.* 2011). Irg1 – pulse irrigation (15 min every 30 min) throughout the day and terminated at 17:00; Irg2 – one daily irrigation event terminated at 9:00; Irg3 - one irrigation event every two days terminated at 17:00 on the first day.

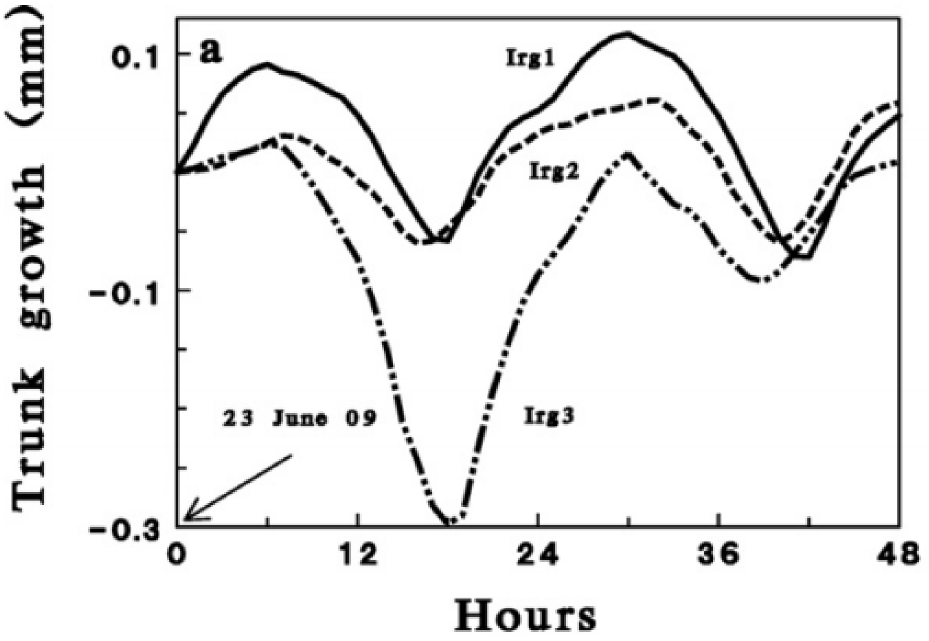


Figure 63 - Trunk growth changes 48 hours, maximum shrinkage with irrigation treatment Irg1 – pulse irrigation (15min every 30min) throughout the day (started at 2:00, terminated at 17:00); Irg2 – one daily irrigation event, started at 2:00, terminated at 9:00; Irg3 – one irrigation event every two days, started at 2:00, terminated at 17:00 (Silber *et al.* 2012).

While daily evaporative demand impacted maximum daily shrinkage as an indicator for tree water stress, the weekly averaged trunk growth rate may be more useful in signifying changes between phenological stages and water requirements (Figure 64) (Silber *et al.* 2019).

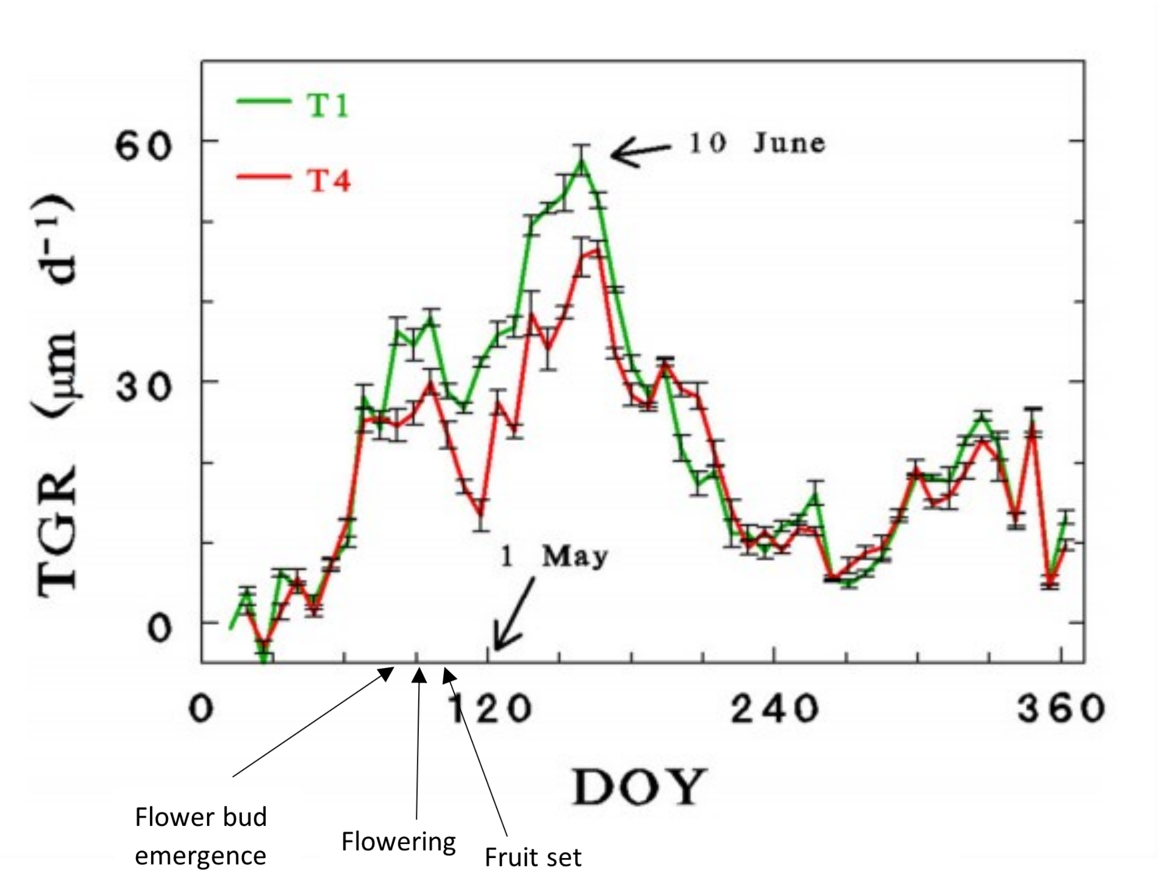


Figure 64 – Weekly averaged trunk growth rate over 2015-2017 experimental years for T_1 and T_2 trees. T1 – no water stress; T4 – no irrigation applied during the early growth period (Jan to May 1) (Silber *et al.* 2019).

Work has been conducted to show that diurnal fluctuations in stem/ trunk diameter are related primarily to the phloem and thus are due to changes in plant water status (Klepper *et al.* 1971). The use of dendrometers for irrigation scheduling is not a straightforward science with the daily trunk growth rate deemed less responsive to changes in plant water status for mature trees or trees holding fruit and the changes in tree physiology throughout the season also playing a part in making interpretation of plant water status readings uncertain (Fernandez & Cuevas 2010).

In another study by Silber *et al.* 2019, it was shown that as long as the ET_0 (Penman-Monteith) was below 5mm / day there was minimal difference in trunk diameter maximum daily shrinkage (MDS) between trees experiencing no water deficit stress (T1) and trees experiencing early growth water deficit stress (T4) (Figure 65). This changes when evaporative demand increases (7mm / day), with T4 showing a significant increase in MDS more in line with the ET_0. In arid areas such as the Tristate where evaporative demand can be high, MDS may be a useful method of measuring changes in tree water status.

Note: As with all equipment calibration is essential to ensure accurate results.

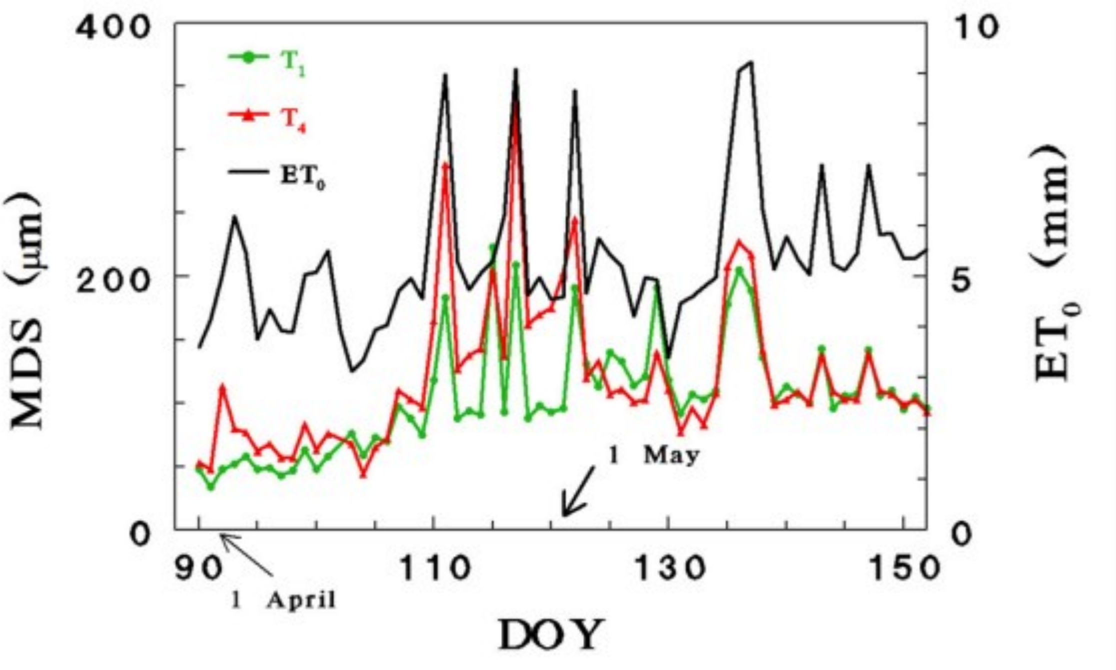


Figure 65 – Maximum daily shrinkage (MDS) of T1 and T4 trees during the first growth period of 2016 (Silber *et al.* 2019). T1 – no water stress; T4 – no irrigation applied during the early growth period (Jan to May 1). ET_0 is calculated using the Penman-Monteith equation.

9.4 Leaf water potential

Leaf water potential (Figure 66) was considered by Moreno-Ortega *et al.* 2019 as a good indicated for water stress in the avocado, though this is not currently very practical to measure.

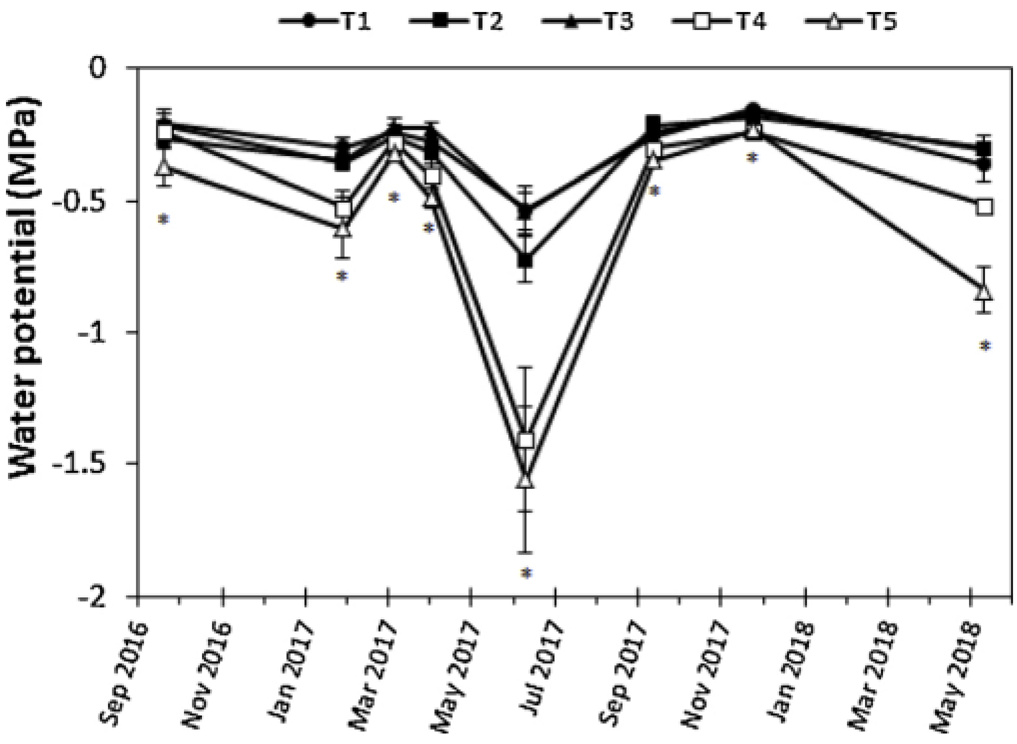


Figure 66 – Leaf water potential for different irrigation treatments (Moreno-Ortega *et al*. 2019). T2 meets water requirements, T4 & T5 approximately 40% below T2. Refer to Figure 51 for treatment volumes.

9.5 Sap flow

Sap flow is another method of monitoring tree water use. Kaneko 2016 demonstrated in their avocado study the sap flow of young versus mature trees in comparison with ET_0 (Penman – Monteith) over a 12-month period (Figure 67) and activity during the different seasons (Figure 68). Given the correlation between sap flow and transpiration, information from sap flow may be useful in developing patterns with environmental conditions, seasonal variation and tree health to form irrigation decisions.

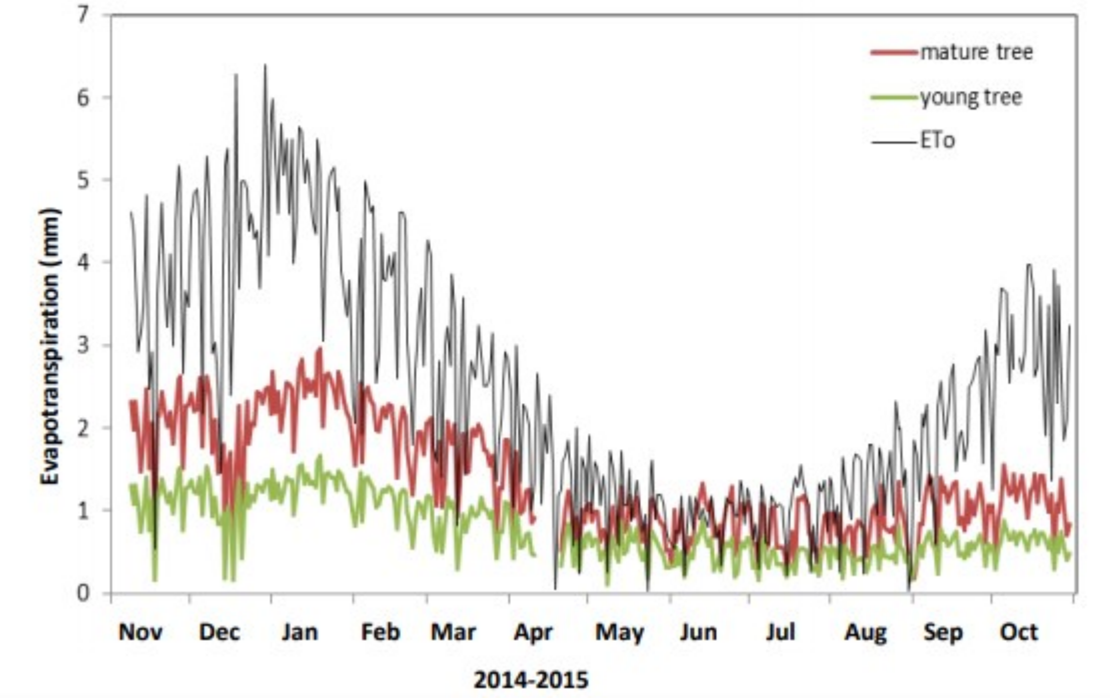


Figure 67 – Daily mean sap flow measurements (evapotranspiration) of tree mature and three young 'Hass' trees and ET_0 as calculated by the Penman-Monteith evapotranspiration equation for 2014-2015 (Kaneko 2016).

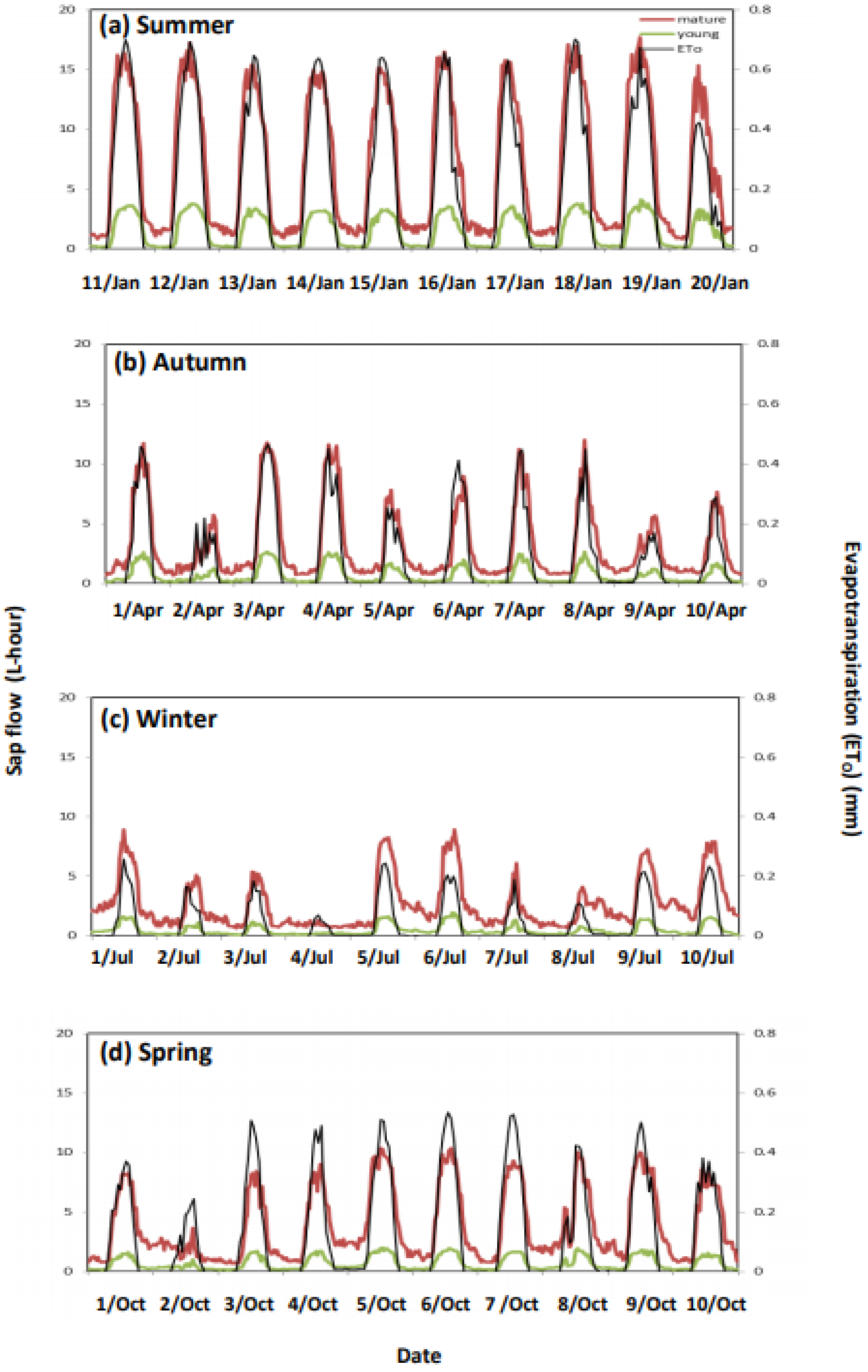


Figure 68 – Hourly mean sap flow measurements of three mature and three young ‘Hass’ trees on typical days in New Zealand for (a) mid-Summer, (b) Autumn, (c) Winter, (d) Spring with ET_0 calculated by the Penman-Monteith evapotranspiration equation (mm/hr) (Kaneko 2016).

9.6 Electrical signals

Electrical signaling measured between avocado roots and the leaves has shown a significant decrease in voltage as a result of root drying and an increase in voltage in response to soil wetting. A change in soil water content of 1.3% resulted in a 96.3% variation of the initial voltage level in 28-56 minutes of the change. The signal was thought to have travelled through the xylem but lower voltage changes and slow signal responses as a result of girdling indicated that the phloem is transmitting the electrical signal from avocado roots to shoots (Gil *et al*. 2008).

Extracellular electrical signals between the stem base and leaves has been shown in avocados to reduce stomatal conductance as a result of soil drying and re-watering. The voltage changes between the root and the shoot in response to changes in soil water content and has been shown to be a communication style used by the avocado. Avocados exposed to only 90 minutes of drought simulated stress saw significantly reduced stomatal conductivity communicated by a change in the root to shoot electrical potential (Gil *et al.* 2008). Could the measurement of internal plant electrical potential be the future for monitoring tree water use and stress?

9.7 Phone Apps

As technology becomes a more integral part of growing avocados, are we looking for smartphone applications to assist in the scheduling of irrigation?

There are already a number of phone apps that calculate and forecast evapotranspiration data including Australian company, The Yield.

Soil moisture monitoring equipment and irrigation controllers are going online in the form of apps. This makes data collection and control of equipment more accessible for informed and timely irrigation decisions to meet tree water requirements.

While there are a number of platforms available e.g. Smartirrigation, they are not all currently available to service Australia.

10. Summary

Irrigating Australian avocado orchards appropriately is a duty of care to ensure environmental sustainability, while effective irrigation is essential to maximise tree health, fruit yield and quality. Both are important to ensure long-term business and industry viability.

When reviewing irrigation practice consider the following points:

- Irrigation scheduling is specific to individual orchards and is reliant on irrigation infrastructure and system type, soil type, rootstock / scion selection, cropping levels, tree size, environmental conditions, and monitoring equipment, etc. The operator can only control the time interval between irrigation events and the water volume applied. The effectiveness of irrigation scheduling and improving best practice will develop from understanding tree water relations specifically physiological and phenological in real orchard time.
- Tree physiological processes change with situations of excess or deficit water; or environmental conditions (e.g. stomatal closure). A roll-on effect directly follows limiting the tree's ability to access nutrients or produce carbohydrates which impacts tree health and production (fruit number, size and quality). Scheduling irrigating to limit a negative change in physiological processes could benefit orchard production.
- Tree phenology changes the volumes of water required by the tree. Irrigation scheduling should be closely linked to the monitoring of tree phenology.
- Calculating water productivity can highlight the opportunities for water savings, differences in water-use between avocado varieties / rootstocks and benchmark individual and industry annual water use.
- Maximising root system growth and health could provide continued function during competition for resources (leaf flushes / fruit growth) and times of water stress. Monitoring root growth regularly by digging holes will provide a timeline for root flushes in your orchard.
- Irrigation during flowering is important to support fruit set and to replace water lost through the increased surface area created by the flowers themselves. Monitoring tree water use during this time is important to meet tree water requirements.
- More information is required to understand the role of water and irrigation scheduling (interval and volume) pre-flowering to support fruit set during flowering and beyond.
- Fruit growth and development is closely linked to the water status of the tree. Water availability is particularly important during the first fruit growth phase for final fruit size. Irrigation interval will impact the final yield results.
- Avocados require an aerobic root environment for maximum growth and production. This environment is flooded each time an irrigation event occurs. While both water and oxygen are important for production, irrigation scheduling that maximises oxygen in the rootzone may benefit orchard production.
- Soil nutrients are not available to the tree without water. Therefore, irrigation and fertigation are linked and informed decisions on how to feed and water trees should be made together not separately; for effective

use of resources. Given the relatively new inclusion of fertigation to some orchards, this may require modifications made to the existing irrigation system or totally new infrastructure.

- Salt is becoming a major long-term production issue for some avocado growers. With no easy solution available, growers are encouraged to investigate salt tolerant rootstocks now and start planning for a variety of scenarios.

- *Phytophthora cinnamomi* and avocados both require aerobic environments making them well suited companions. While Phytophthora root rot does not require free water for infection, the use of irrigation is making it easy for the pathogen to travel to the host and spread within the orchard. Flooding in the presence of *Phytophthora cinnamomi* negatively impacts tree health greater than the two factors experienced separately and flooding should be avoided in avocado orchards. More work is required to determine if modifying irrigation intervals or water volumes could reduce Phytophthora root rot activity.

- Irrigation interval and volume will influence the level of soil biological activity.

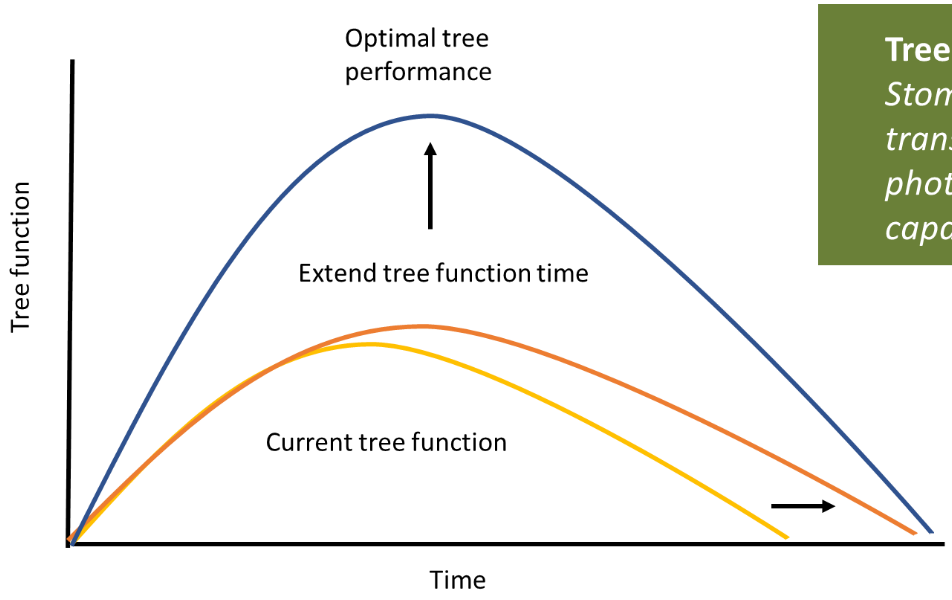
- Orchard water use efficiency can be improved by using soil or plant-based monitoring equipment; providing information on which to make informed irrigation decisions. As with all equipment - understanding the information recorded, calibration and field monitoring is recommended to ensure the information irrigation decisions are based upon is relevant, accurate and reliable.

- Smartphone apps are allowing data to be only a finger tap away ensuring timely irrigation decisions to meet tree water requirements.

11. Closing

Developing a better understanding of tree water relations and tree function in real time will provide information and data to target avocado irrigation management decisions, reducing reaction times and better meeting tree water requirements through irrigation manipulation of the orchard environment.

Figure 69 imagines tree function under current irrigation best practices (yellow line) and the opportunity to extend tree function time through more informed irrigation decisions (orange line) but ultimately the objective of changing irrigation management is to optimise tree performance (blue line) increasing photosynthetic capacity and the ability to build carbohydrates to support tree health, fruit yield and quality through irrigation best practice.



Tree Function = *Stomatal function, transpiration and photosynthetic capacity.*

Figure 69 - Maximising tree function time and tree performance through irrigation best practices (L. Singh 2020).

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