Irrigation of avocado in South Africa: A review

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ABSTRACT

With the increase in water scarcity it becomes increasingly important to look at ways of irrigating avocado orchards more efficiently. This review places the past research and other international literature into context to highlight gaps in knowledge that should be addressed in order to improve the current water management of avocado orchards in South Africa. Research carried out during the 1990s established the current soil-based irrigation norms. However, soil measurements do not supply a direct indication of plant water status, creating a measure of uncertainty if irrigation is applied according to the needs of the tree. Stress was shown to have negative effects on plant performance, yield and post-harvest fruit quality. It is therefore important to revise the water requirement of avocado for the different production regions, as well as to determine the stress threshold levels. In addition, determining water requirements of young, non-bearing orchards is crucial as there are no guidelines for water management of young non-bearing trees.

INTRODUCTION

South Africa is a water-stressed country and faces a challenge in supplying sufficient water to all economic sectors, as well as environmental degradation and water pollution. It is therefore critical that this limited resource is managed as carefully as possible to enable all sectors of the economy to receive a sufficient amount of water. According to the National Water Resource Strategy of 2004, the total water requirement for the country was 12 871 million cubic meters per annum, of which 62% of that requirement was for irrigation purposes. It was further stated that the country's available water resources are virtually fully utilised. As the largest and least efficient water user, irrigated agriculture can expect pressure to reduce water use to make more water available to other economic sectors, which are also expanding and require increasing amounts of water. As the avocado industry is fully dependent on supplementary irrigation, this industry will not be excluded from possible requirements from government to reduce water use.

The questions to be asked are whether current irrigation practices used by avocado growers are optimal, or whether there is room for improving water use efficiency and productivity for the avocado sector. Improving water use efficiency and productivity will not only result in water and cost savings to the grower, but will also result in sustainable future expansion of the industry (current expansion is approximately 500 ha of new plantings per annum). This review is therefore aimed at providing a comprehensive overview on past local irrigation research and identifying gaps in current knowledge to be addressed in potential future research that would be aimed at improving and optimising water use efficiency and productivity for local avocado producing areas.

Why re-looking at current irrigation norms?

During the 1990s a number of studies were carried out and irrigation norms were proposed (Kruger, 2001). These will be referred to later in this review. According to these norms, a grower should not allow more than 50% to 60% depletion of the easily available water of the soil in the effective root zone of trees to avoid plant stress. This corresponds to tensiometer readings (300 and 600 mm depths) not exceeding -35 kPa in a clay soil and -30 kPa in a sandy soil.

The major pitfall of the soil-based irrigation norms is that scheduling is carried out according to the properties of the soil, while the water status of the plant is not taken into consideration (Jones, 2004). No plant water status measurements were made during the irrigation studies of the 1990s (Hoffman & Du Plessis, 1999) and an assumption is therefore made that the plant would not stress if kept within the recommended ranges of soil water content (usually field capacity and 50% depletion of easily available water). There is therefore some measure of uncertainty if the norms set during the 1990s are optimal. In addition, norms set during the 1990s were based mainly on the rootstocks used during that time, which was 'Duke 7'. The question to be considered is if the same norms can be assumed for 'Dusa' 'Bounty' or 'Velvic'. It was clearly shown that scion water use was different on different rootstocks (Fassio *et al*., 2009). Lastly, the effect of climate change is a reality and it will affect rainfall and water distribution patterns considerably in future (Benhin, 2006; Bellprat *et al*., 2015). This includes the local avocado-producing areas, which are predicted to become drier in future. It is therefore crucial to immediately start investigating means of mitigation and adaption to the effects of climate change by looking at interventions for the improvement of water use efficiency of avocado orchards and reduce water use. Growers can very soon expect pressure from government to reduce water use. This is, firstly, because agriculture uses most of the country's surface water (almost two thirds), while it is the least efficient water user. Secondly, the demand for water by other economic sectors, which are often more efficient water users, is increasing (National Water Resource Strategy, 2004; Nieuwoudt *et al*., 2004).

Apart from investigating methods to improve water use efficiency, the next question is whether it is known how much water an avocado tree requires. Water requirement is dependent on cultivar/rootstock, climate, tree age and phenological stage (Ben-Ya'acov & Michelson, 1995; Silber *et al*., 2012). A study was carried out in the Crocodile River basin area where the annual water requirement of bearing avocado trees was determined as 9 825 m^3/ha/annum (Hoffman, 1999). The methodology for this study was unfortunately not discussed in the report. In addition, this study was only carried out in one area and it is in all likelihood not applicable in other important avocado producing areas. There is therefore a need to re-look at this aspect and determine orchard water use and model this water use to enable extrapolation to other areas.

An important gap in current knowledge on avocado tree water requirement is the water requirements of young non-bearing avocado trees. Internationally, no irrigation guidelines for young trees are available, which implies that irrigation of new plantings is made on intuition with a risk of continuous over- or under-irrigation. Water requirements of young trees from planting to first crop will depend on the climatic conditions and leaf area index of the tree (Lahav & Whiley, 2002). Modelling should therefore include these aspects when water requirements of young non-bearing orchards are determined.

To conclude this section:

- It is firstly important to note that irrigation research of other avocado-producing countries cannot be applied to our local conditions, due to differences in climate, soil and cultivar/rootstock combinations. Irrigation norms therefore have to be determined for our local conditions.
- Current irrigation norms are based on soil-based measurements only, which do not give a direct indication of tree water requirements. There is therefore a need to determine avocado water requirements for bearing avocado trees.
- It is especially important to determine water requirements for young trees from planting to first crop as there are currently no irrigation guidelines available for young non-bearing avocado trees.
- Water requirement determinations should be carried out for the different phenological stages. The importance of this will be discussed in the next section.

Water requirements at different phenological stages

It is important to note that different phenological stages differ in their water requirements. Preliminary data obtained from DFM probes clearly showed that water withdrawal patterns differ considerably during different phenological stages (Roets *et al*., 2013). Although little research was carried out on the determination of water requirements during different phenological stages, there was considerable work carried out on the effect of stress during different phenological stages. This will be briefly discussed.

- **Vegetative growth:** Shoot growth and flushing are directly related to water availability. Low water availability resulted in a reduced number of flushes per annum, reduced leaf area, reduced shoot length and trunk growth, lower canopy volume, reduced plant dry weight and reduced volume of fibrous roots (Faber *et al*., 1995; Chartzoulakis *et al*., 2002; Lahav & Whiley, 2002). It was also shown that 'Hass' was more sensitive to stress than 'Fuerte' (Chartzoulakis *et al*., 2002). This emphasises the need to study cultivar-specific water requirements.
- **Flowering:** Avocado trees usually flower profusely (up to a million flowers per tree), but less than 0.1% of these will eventually set fruit (Scora *et al*., 2002). The flowers contain stomata and during full bloom, transpiration rates of flowers are higher on an area basis than transpiration rates of leaves (Blanke & Lovatt, 1993). According to Whiley *et al*. (1988) the contribution of floral transpiration to the total water requirement of the tree is approximately 13%, implying some increase in water requirement during flowering. Full flowering under local conditions usually occurs during September (i.e., early spring) and it is a time when high temperatures coupled with low humidity are prevalent. Night temperatures on the other hand might still be low, resulting in soil temperatures being relatively low during this time. It was shown that root activity was impaired at soil temperatures lower than 13°C (Hofshi, 1996). The high temperature and low humidity conditions coupled with low soil temperatures may therefore create a situation where the transpiration demand is very high with the root system not being capable of supplying the high transpiration demand. This may result in considerable stress, which may lead to flower and young fruitlet abscission as well as leaf abscission. The negative effect of heat stress, prevalent under the above-mentioned conditions, was reported in a study carried out by Lomas (1992). It is therefore crucial to investigate ways of mitigating stress during this time to ensure decent fruit set.
- **Early fruit growth:** Evidence from a number

of fruit crops showed that potential yields are set during the early, intense cell division stage of fruit growth due to the availability of energy reserves at that time (Wolstenholme, 1987). For avocado, heavy fruitlet abscission occurs from flowering to the stage of initial cellular enlargement (Silber *et al*., 2012). This excessive fruitlet abscission is influenced by three factors, namely competition between young fruit and vegetative growth, sensitivity to temperature extremes and water stress (Lovatt, 1990; Silber *et al*., 2013) or a combination of these factors. In addition, before developing fruit reached 10 g, transpiration of the fruit exceeded that of respective leaves on a surface area basis (Blanke & Whiley, 1995). In South Africa, avocado display a fruit drop period during November that is commonly termed as "November drop" where a large number of fruit of approximately 10 g in weight are abscissed. At this stage it might be speculated that water stress imposed by transpiring fruit coupled with low water availability could initiate fruit abscission. However, currently the exact mechanism of fruitlet abscission in avocado is not yet well understood (Silber *et al*., 2013) and this is therefore a field for further investigation. Water stress during fruit set and early fruit development may therefore result in reduced yields or even crop losses. It is possible that low water availability may negatively affect fruit size (Lahav & Steinhardt, 1992), although some workers found that fruit size was rather correlated to number of fruit per tree and not to the irrigation applied (Michelakis *et al*., 1993; Faber *et al*., 1994; 1995). However, it was clearly shown that water availability had a marked effect on daily fruit growth rates (Silber *et al*., 2013) and that fruit size was negatively affected by low water availability (Roets *et al*., 2015).

- **Yield:** It was shown that the transpiration water that actually passes a crop is linearly related to yield levels (Gerbens-Leenes & Nonhebel, 2004). Work carried out in Israel, showed a significant correlation between irrigation water application and relative yield. In this study it was shown that for a 1 000 m^3/ha reduction in the water requirement of the tree, a yield reduction of approximately 2.2 ton/ha and 1.6 ton/ha was obtained for 'Hass' and 'Fuerte' respectively. This corresponded with approximately 20% yield loss. No crop was obtained below a certain threshold value (Lahav & Steinhardt, 1992). Locally, it was found that the highest accumulative yield can be obtained when soil matric potential is kept at approximately -40 kPa for a clay soil (Van Eyk, 1994). The most favourable effect on yield and fruit size was found if the matric potential of clay soil be kept between -25 and -35 kPa. These levels also corresponded with the least stress (optimal transpiration and photosynthesis) (Roets *et al*., 2015).
- **Post-harvest fruit quality:** Pre-harvest water stress was shown to affect post-harvest ripening and quality. Water stress, as a result of low soil water content or variation in soil water content due to soil heterogeneity, was delayed and produced uneven post-harvest fruit ripening (Kruger & Magwaza, 2012; Kruger *et al*., 2013; 2015) as well as higher incidences of the post-harvest physiological disorders grey pulp and pulp spot (Bower *et al*., 1989). Under conditions of dry-land production, uneven ripening was further exacerbated (Kruger & Magwaza, 2012) and dry-land production of avocado under local conditions is therefore not feasible. In addition, faulty irrigation designs also resulted in considerable uneven ripening due to trees in an orchard receiving different amounts of water during irrigation (Kruger & Lemmer, 2014). Supplementary irrigation further resulted in higher oil content of fruit (Kruger & Claassens, 1996; Lahav & Whiley, 2002), but this was dependent on irrigation interval in which shorter irrigation intervals resulted in higher oil content (Lahav & Kalmar, 1977; Lahav & Whiley, 2002).
- **Other water stress related fruit disorders:** A fruit disorder ascribed specifically to water stress that occurs on avocado is a blemish, usually on the fruit stem, termed ring-neck. This is characterised by irregular superficial dried tissue, which becomes separated from the pedicle, leaving a scar (Hofshi & Arpaia, 2002). As it is superficial, it might not affect nutrient, water and photo-assimilate transport to the fruit and it is therefore more likely that any disorders of the fruit are directly related to water stress and not due to ring-neck. However, in an earlier study it was shown that ring-neck may occur on the fruit close to attachment of the fruit stalk to the fruit (Storey *et al*., 1973), which negatively affected fruit marketability.

From this section it can be concluded that water stress at any phenological stage will eventually have an adverse effect on yield and post-harvest fruit quality. This will lead to a decrease in the marketability of the fruit and subsequent financial losses. To avoid water stress at any phenological stage, it is therefore crucial that water requirements for each phenological stage be determined and specified.

The avocado root system and the effect of irrigation on root distribution

Due to evolutionary adaptations in a rainforest environment, avocado trees developed a shallow, extensively suberised, relatively inefficient root system with low hydraulic conductivity (Wolstenholme, 1987). Even though the root system is relatively inefficient as described, it was shown that it is completely capable of providing the transpiration demand of the tree canopy under most conditions, if soil water content remains close to field capacity (Sharon *et al*., 2001).

In an orchard situation, however, root depth and spread is mainly dependent on the soil type, drainage, irrigation system and irrigation intervals (Lahav & Whiley, 2002). Root distribution from the trunk is more or less uniform in a clay soil, while diminishing from the trunk outwards in a sandy soil. Roots were also found further away from the tree trunk in a sandy soil compared with a clay soil. Most of the roots (approximately 40%), regardless of soil type, are less than 2 mm in thickness. Both roots of less than 2 mm and 2 to 5 mm were found in the first 20 cm in a sandy soil, while the less than 2 mm roots were in the first 20 cm in a clay soil and the 2 to 5 mm roots were distributed from 0 to 60 cm. Roots thicker than 8 mm were not found deeper than 40 cm in a clay soil while they were distributed up to 1 m deep in a sandy soil (Salazar-Garcia & Cortes-Flores, 1986). Salgado & Cautin (2008) also found that root frequencies increase proportionately with the sand fraction of the soil, regardless of irrigation system. In an early study carried out by Rowell (1979), it was found that though most of the roots were found in the top 600 mm of the soil profile, roots deeper than 900 mm were also found that were capable of withdrawing water from the soil. Further, roots tend to be deeper in areas receiving high rainfall compared with drier areas (Salgado & Toro, 1995). Soil bulk density has a major influence on root distribution. When soil bulk density was greater than 1.7 g/cm^{-3}, it became unsuitable for root growth. Transition from a soil horizon of relatively low density to one with a relatively high density restricted root growth to a certain extent (Durand & Claassens, 1987). Under South African conditions, two root growth periods occur. The first at the end of summer and the second at the end of winter (Moore-Gordon & Wolstenholme, 1996).

The irrigation system used, also has a major influence on root distribution. In a study carried out by Michelakis *et al*. (1993), it was found that root distribution in a drip irrigated avocado orchard depended on the wetted area of the soil, soil water content and soil aeration. 70 to 72% of the roots were found in the top 500 mm of the soil profile and this was mainly influenced by soil aeration. In addition, root density was the highest in a radius of 2 m from the emitter and was dependent on the wetting pattern of the emitter and soil water content. In another study, under micro-irrigation in coarse soil, roots tended to be close to the tree trunk with most roots not found deeper than 250 mm from the soil surface, whereas in a fine soil, roots were also found close to the tree trunk but deeper at about 500 to 600 mm from the soil surface. For drip irrigation in the coarse soil, roots were also shallow (200 mm from the surface), while much deeper (up to 750 mm) in a fine soil (Salgado & Cautin, 2008). This is because water will penetrate much deeper in the fine soil compared with to the coarse soil.

Infection with *Phytophthora cinnamomi* root rot results in considerable loss of roots, leading to compensatory loss of leaves, lower leaf water potentials, reduced stomatal conductance and therefore lower photosynthetic activity and disturbed mineral uptake. This negatively affected tree health and production (Wolstenholme, 1987). It was found that trees infected with *Phytophthora cinnamomi* root rot had virtually no roots in the deeper soil layers (900 mm) compared with healthy trees (Durand & Claassens, 1987). Prolonged wet conditions (wetter than field capacity) with accompanying poor aeration is conductive to and enhances the occurrence of *Phytophthora cinnamomi* root rot (Schaffer & Ploetz, 1989; Ben-Ya'acov & Michelson, 1995; Lahav & Whiley, 2002).

To conclude, even though 70 to 80% of the roots are found in the first 600 mm of soil profile (Lahav & Whiley, 2002), avocado roots may penetrate deeper than 1 m, implying that the root system is not necessarily shallow under all conditions. But when the root system is shallow due to restrictions, it could temporarily fail to supply the high demands for water and nutrients during critical phenological stages, such as flowering, fruit set or seed development (Silber *et al*., 2012), especially under conditions of low soil temperature (see earlier discussion). Root activity can further be lowered by poor soil aeration and infection with *Phytophthora cinnamomi* root rot. The effect of poor soil aeration by flooding on the root system and the tree will be discussed in the following section.

Effect of flooding

For avocado roots to function optimally, oxygen is needed for root respiration, and trees should therefore be planted in well-aerated soils. It was shown that when soil air content dropped below 17%, avocado root functioning was impaired (Ferreyra *et al*., 2007). Under conditions of flooding, oxygen is displaced by the water from the soil, resulting in oxygen starvation or anoxia, which is detrimental to the roots. Only a few days of flooding conditions will severely damage or kill trees – avocado trees are therefore not flood tolerant (Balerdi *et al*., 2003). Root death due to anoxia is caused by the accumulation of toxic by-products (mainly ethanol and acetaldehyde) of anaerobic respiration in the vicinity of the roots (Schaffer, 2006). Root death and impaired root functioning caused by flooding will result in plant stress, as water and mineral uptake is hampered. Stress symptoms are similar to drought stress, with declined rates of photosynthesis, transpiration and decreased stomatal conductance (Schaffer & Ploetz, 1989; Schaffer, 2006; Reeksting *et al*., 2014). Even though avocado is flood-sensitive, there is a certain extent to which short term flooding can be tolerated, but it depends on a number of factors, namely the rootstock, crop load, air temperature, flood depth and duration (Balerdi *et al*., 2003). Young trees are usually more sensitive to flooding and drought stress than mature trees (Balerdi *et al*., 2003). It is, however, possible that an orchard subjected to flood conditions can recover and the following measures were recommended by Balerdi *et al*. (2003):

- Remove a portion of the tree canopy, as this will reduce the transpiration load from the root system, which could be significantly reduced by the flooding. This is to prevent the remaining leaves from desiccation and death. This was proven in a later study in which case pruning of the canopy directly after flooding resulted in quicker recovery

of the tree (Sanclemente *et al*., 2014).
- Fruit should be removed as fruit increases the effect of the flooding stress.
- Wait for several weeks to evaluate damage as trees take several weeks to recover from stress.

In general, it is recommended that areas prone to flooding should be avoided, but if not possible, trees can be planted on ridges to allow proper drainage of soil and prevent flooding from reaching the root zone of the trees (Balerdi *et al*., 2003). Ridges, however, have the disadvantage of larger soil temperature fluctuations, which may affect root functioning negatively under certain conditions (Benjamin *et al*., 1990). Ridges therefore will be beneficial only in areas where flooding prevails, but would be unnecessary in areas with well-drained soil.

The effect of salinity

Although not an important factor under South African conditions, it would be worthwhile to mention the effects of salinity on avocado production. Avocado trees are considerably sensitive to salinity (Musyimi *et al*., 2007). Visual symptoms caused by chloride toxicity are characterised by leaf tip burn, which progresses basipetally and sometimes along leaf margins. Visual sodium toxicity symptoms are characterised by necrotic spots near the margin or interior surface of the leaf (Whiley & Schaffer, 1994). Effects of salinity on the physiology of the plant are comparable with other forms of stress. These effects include reduced stomatal conductance, transpiration, photosynthesis, leaf chlorophyll content, leaf water potential and water use efficiency, while increased sub-stomatal CO_2 concentrations were evident (Salazar-Garcia & Larque-Saavedra, 1985; Musyimi *et al*., 2007). Negative effects of salinity on tree growth included decreased root growth, delayed appearance of new flushes, smaller leaves and reduced yields (Lahav & Steinhardt, 1992; Bernstein *et al*., 2004; Musyimi *et al*., 2007). Stress is mainly the effect of reduced water uptake as well as altered mineral uptake. Trees were completely unable to extract water from the soil when the electrical conductivity of the soil reached values of 4 $dS.m^{-1}$ or higher (Crowley, 2008).

In countries such as Israel that are very prone to saline conditions, trees are planted on West-Indian rootstocks as they are more resistant to salinity than Mexican rootstocks (Ben-Ya'acov & Michelson, 1995). In general, salinity is a problem in semi-arid production areas with low rainfall and poor water quality, resulting in salt accumulation in soil (Whiley & Schaffer, 1994). Under South African conditions, rainfall in avocado-producing areas is in general high and salt accumulation in the soil is therefore less likely to occur.

Why plant-based measurements for determining water requirements and optimizing irrigation scheduling?

To ensure optimal plant performance and prevent stress, it is important that the water status of the plant is known. It would therefore make sense to measure plant water status for irrigation scheduling purposes. However, carrying out plant-based measurements on-farm is mostly impractical, due to cost, difficulty in automation, the fact that it is labour-intensive and requires skilled labour and difficulties in data interpretation (Goldhamer & Fereres, 2001; Jones, 2004). The result was that plant-based measurements were used only in research studies. A recent research study focussed on calibrating the current soil-based irrigation norms using midday stem xylem water potential, other plant physiological indicators, fruit set, fruit size and yield (Roets *et al*., 2012; 2013; 2014; 2015). Results of this four year study indicated that soil matric potential should be kept between -25 and -35 kPa. Within this range, it was shown that plants do not experience stress and that the most favourable effect on yield and fruit size distribution was obtained. Midday stem xylem water potential was specifically selected as it was shown to be a reliable indicator of plant water status in a number of crops and was useful for the indication of irrigation requirements of those crops (Naor, 2000).

One of the major disadvantages of water potential measurements is that it is based on single leaf measurements. It was found in a study with mesquite, using sap flow and porometer measurements, that when transpiration is high, accuracy of scaling porometer leaf measurements to stem measurements declined. The position of the leaves in the canopy also resulted in the differences between sap flow and porometer measurements. The number of leaves measured with the porometer contributed further to variation (Ansley *et al*., 1994). It was also shown by Zang *et al*. (1997) that using single leaf measurements has a major shortcoming in determining tree water requirements, due to variation created by the spatial distribution of leaves on the tree. It would therefore be important with determination of tree water requirements that it be carried out on a whole tree level or at orchard scale level.

A popular approach to determine tree water requirements on a whole tree level is through the use of sap flow measurements. This was shown to provide a highly reliable indication of whole tree transpiration and is therefore very useful to study plant water relationships (Zang *et al*., 1997). Only one study with sap flow measurements on avocado could be found. In this study it was shown that rootstock has a significant effect on sap flow and therefore transpiration rate of 'Hass' avocado (Fassio *et al*., 2009). This strongly emphasises the need to re-look at water and irrigation requirements for the rootstocks that are currently used.

In most instances, plant measurements are combined with other measurements, such as soil water content and meteorological data, in order to estimate whole orchard water usage. The data collected is then used to test or design models that can be used to predict orchard water use or for extrapolation to predict orchard water use of different regions and to optimise crop factors (Taylor & Gush, 2014). Any future study for determination of water requirements for avocado will make use of this approach to estimate water use for the different production areas.

CONCLUSION

Considering this review, there is a clear need to quantify the water use of avocado in relation to yield at orchard level. To achieve this, it would firstly be necessary to measure water use of unstressed avocado trees at different phenological stages, from planting to mature canopy size, for selected cultivar/rootstock combinations and locations. After measuring the water use, the data collected should then be used to model unstressed water use of avocado, according to phenological stages from planting to mature canopy size for the selected cultivars and locations. The influence of stress during different phenological stages on yield and fruit quality must also be assessed. Lastly, the water use efficiency and water use productivity of avocado for selected cultivars and locations should be quantified.

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