Quantifying water movement in soils irrigated by continuous drip irrigation with Citrus in the Western Cape

by

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Declaration

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Summary

The development of low discharge rate emitters by Netafim opened new possibilities to approach irrigation and fertilization and introduced continuous low flow drip irrigation, allowing for intensive management of fruit production on difficult to manage soils. This entails decreasing the application rate of the irrigation system to balance with the maximum daily water use over the total consumptive period of the crop addressing many challenges in managing irrigation in an orchard. A key for efficient drip irrigation is to adjust the shape of the wetted soil volume created under an emitter to the main root distribution, which is well known for conventional drippers in different soil types, but not for low flow continuous drip irrigation.

In this study the daily water requirement of young 'Nadorcott' mandarin citrus trees were applied in three continuous drip irrigation treatments with different drip discharge rates (T1-0.4L.h^{-1}, T2-0.7L.h^{-1} and T3-1.6L.h^{-1} allowing different irrigation cycle lengths, to study the effect on soil water content distribution, root distribution and crop response .

T1-0.4L.h^{-1} maintained an average higher SWC in the active root zone along the season followed by T2-0.7L.h^{-1} and T3-1.6L.h^{-1} respectively. Significantly higher SWC was observed close to the soil surface with T1-0.4L.h^{-1} followed by T2-0.7L.h^{-1} and T3-1.6L.h^{-1} respectively. Relative average lower SWC with daily conventional irrigation was expected due to narrower spacing of drippers and lower volume of water applied per emitter.

2-Dimentional water distribution patterns parallel and across the ridge showed that T1-0.4L.h resulted in a smaller wetted soil volume compared to T2-0.7L.h with less horizonal and vertical water distribution from an emitter, which may have encouraged fibrous roots to grow closer to the soil surface and to the tree. More overlap was observed in T2-0.7L.h parallel with the ridge resulting in greater vertical distribution of water between two adjacent drippers where wetted soil volumes merge which favoured roots to grow and proliferate deeper down the soil profile and further away from the tree. A wetted strip was formed under T3-1.6L.h due to narrower spacing of drippers, compared to the 'pots' formed with T1-0.4l.h and T2-0.7L.h, resulting in a dense root strip across the profile in the 20 to 40cm depth. Highest fine root density was recorded in T3-1.6L.h in the 20 -30 cm layer,

followed by T2-0.7L.h in the 30 to 40 cm layer and T1-0.4L.h in the 20-30 cm layer respectively.

A bimodal distribution of water was observed in T1-0.4L.h and T2-0.7L.h early in the morning when a shorter irrigation event took place characterized by a main wetted soil volume in the upper 50 cm and concentrated areas of higher soil water content in the lower 50 cm. Approaching midday as irrigation continued SWC in the main core of the wetted soil volume increased and lower SWC was observed in the rest of the soil profile indicating a 'shrinking' of the wetted bulb midday after which a bimodal water distribution resumed. T3-1.6 showed very little fluctuation during the day. It seems as if the antecedent soil water content may contribute largely to soil water content fluctuation and distribution patterns. Overall little fluctuation of the wetted soil volume was observed daily, maintaining very constant SWC levels in the root zone.

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Opsomming

Die ontwikkeling van lae lewering druppers deur Netafim het nuwe moontlikhede mee gebring om besproeing en bemesting deur die dripstelsels te benader en het deurlopende lae vloei drupbesproeing bekendgestel aan landbou wat intensiewe bestuur van gewasproduksie op voorheen moeilik bestuurbare grond vir besproeing moontlik maak. Hierdie konsep behels om die lewering van die besproeingstelsel te verlaag om te balenseer met die maksimum daaglikse waterverbruik oor die totale waterverbruiksperiode van die gewas, wat vele uitdagings van besproeingsbestuur van 'n boord aanspreek. 'n Sleutel tot effektiewe drupbesproeing is om die vorm van die benatte grond volume wat onder 'n drupper vorm so te bestuur om ooreen te stem met die hoof wortelverspreiding, wat wel bekend is vir tradisionele hoër lewering druppers, maar nie vir deurlopende lae vloei drupbesproeing nie.

In hierdie studie was die daaglikse water behoefte van jong 'Nadorcott' sitrus bome toegedien deur drie deurlopende drupbesproeing behandelings met verskillende drup lewering (T1-0.4L.h^{-1}, T2-0.7L.h^{-1} en T3-1.6L.h^{-1}) wat drie bespoeingsikluslengtes toegelaat het om die effek op grondwaterinhoudsverspreiding, wortelverspreiding en gewasreaksie te ondersoek. T1-0.4L.h^{-1} het 'n gemiddelde hoër grondwaterinhoud in die aktiewe wortelsone gehandhaaf met die verloop van die seisoen gevolg deur T2-0.7L.h^{-1} en T3-1.6L.h^{-1}onderskeidelik. Beduidende hoër grondwaterinhoud was nader aan die grondoppervlak geobserveer met T1-0.4L.h^{-1} gevolg deur T2-0.7L.h^{-1} en T3-1.6L.h^{-1}onderskeidelik. Relatiewe laer gemiddelde grondwaterinhoud met T3-1.6L.h^{-1} was verwag asgevolg van die nader spasiering van druppers en laer volume water wat per drupper, toegedien word. 2- Dimensionele waterverspreidingspatrone parallel and loodreg met die rif het aangetoon dat T1-0.4L.h^{-1} 'n kleiner benatte grondvolume tot gevolg gehad het in vergelyking met T2-0.7L.h^{-1} met minder horisontale waterverspreiding vanaf 'n drupper, wat fynwortels kon aangemoedig het om nader aan die grondoppervlak en die boom te groei. 'n Groter mate van oorvleuel van benatte grondvolumes parallel met die rif was geobserveer met T2-0.7L.h^{-1} wat gelei het tot meer vertikale verspreiding van water waar benatte grond volumes oorvleuel het, wat wortel aangemoedig het om dieper in die grond profiel te groei en verder weg vanaf die boom te versprei. 'n Benatte strook het

gevorm met T3-1.6L.h^{-1} asgevolg van die nader spasiering van druppers, in vergelyking met die benatte ‘potte’ wat gevorm het met T1-0.4L.h^{-1} en T2-0.7L.h^{-1}, wat gelei het tot ‘n wortelstrook regoor die profiel tussen aangrensende bome in die 20 tot 40 cm diepte. Hoogste fynworteldigtheid was geobserveer met T3-1.6L.h^{-1} in die 20-30 cm laag, gevolg deur T2-0.7L.h^{-1} in die 30-40cm laag en T1-0.4L.h^{-1} in die 20-30 cm laag onderskeidelik.

‘n Bimodale waterversreiding was waargeneem in T1-0.4L.h^{-1} en T2-0.7L.h^{-1} vroeg in die oggend met die aanloop van’n ‘korter’ beproeing siklus, met ‘n hoof benatte grondvolume in die boonste 50 cm and gekonsentreerde areas van hoër grondwaterinhoud in die onderste 50 cm. Met die aanloop na middag soos besproeing verloop het, het die grondwaterinhoud in die ‘kern’ van die hoof benatte grondvolume toegeneem en laer grondwaterinhoud was in die res van die profiel opgemerk wat ‘ krimping’ van die benatte grondvolume toon oor middag. Soos die dag verloop het was ‘n bimodale verspreding van water weer waargeneem na middag. T3-1.6L.h^{-1} het baie min verandering gedurende die dag getoon. Dit bleik dat voorafgaande grondwate inhoud voor ‘n besproeingsiklus begin moontlik ‘n groot effek het op grondwater fluktuasie en waterverspreidingspatrone. Oor die algemeen was die daaglikse verandering in grondwaterinhoud minimaal met al drie behandelinge en het konstante hoë grondwaterinhoud vlakke in die wortel sone gehandhaaf.

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Chapter1: General Introduction and Project Aims

Due to its highly localized water and nutrient application, drip irrigation has gained widespread recognition and acceptance as an efficient irrigation method (Elmaloglou, Soulis and Dercas, 2013). The introduction of drip irrigation to citrus production opened new possibilities to approach irrigation and fertilization and catalysed innovation for intensive management of fruit production on previously unsuited soils (Rawlins and Raats, 1975; Falivene, 2005).

Known for its lower application rates and increased water use efficiency compared to conventional irrigation methods (Panigrahi and Srivastava, 2016; Andreu, Hopmans and Schwankl, 1997; Selim *et al.*, 2013), leaching remains a concern, especially on low water holding capacity soil such as sandy and rocky soils (Phogat *et al.*, 2014; Andreu, Hopmans and Schwankl, 1997). To simultaneously meet crop water demand and prevent leaching beneath the root zone, an irrigation management practise known as pulsing has been the approach using traditional 3.5, 2.3 and 1.6 Lh^{-1} drippers (C. Malan, personal communication) that entails a few short irrigation cycles per day, composed of an irrigation phase and a resting phase (Phogat *et al.*, 2013). This practice aims to maintain water and consequently nutrients, when fertigating, within the active root zone, minimizing excess movement of the waterfront beyond the dense root mass (Elabadin, Ibrahim and Omara, 2014) associated with citrus trees irrigated via drip irrigation (Castle, 2015; Kafkafi and Tarchitzky, 2011; Falivene, 2005).

The filling and emptying of the irrigation system associated with pulse irrigation can lead to over and under irrigation in an orchard even when irrigation is applied with pressure compensated drippers (Netafim). Managing irrigation for a restricted root zone in a sandy soil, up to nine or more pulses could be scheduled throughout the day in summer managing soil water content (SWC) at a 10% extraction of readily available water (RAW) (Falivene, 2005). This may result in increased pump cost, maintenance and labour and may lead to ununiform orchards in terms of growth and yields (C. Malan, personal communication). With so many pulses per day a continuous form of irrigation application by low output drippers would be essential to maintain the desired soil moisture level (Falivene, 2005)

.Lowering application rate would imply that the same amount of water can be applied continuously at a lower rate in one irrigation shift, stretched over a longer period. With the development of low discharge rate emitters by Netafim, such an irrigation approach known as continuous drip irrigation or low flow drip irrigation is introduced to perennial crop production (C. Malan, personal communication).

The total planted area of late maturing mandarins increased with 21% from 2014 to 2015, more than any other cultivar group (Cronje, 2016), accompanied by drip irrigation and fertigation practises and became a popular research field emphasized by the majority of citrus and irrigation practise literature available (Kadyampakeni *et al.*, 2014; Falivene, 2005; Syvertsen and Jifon, 2001). According to the water wheel article (July 2018 edition) the Western Cape contributes the most to total area irrigated, followed by Limpopo with an average water use of 5874 m^3. ha^{-1} and 8841 m^3. ha^{-1} for each province respectively. To increase water use efficiency and sustainable water use, drip irrigation can play a major role. One of the key principals of drip irrigation contributing to more efficient and sustainable water use is introducing the applied water directly to the root zone (Phogat *et al.*, 2014; Bravdo and Proebsting, 1993). To further improve on irrigation practices of low flow drip irrigation, knowledge of the distribution of water in the soil profile in relation to the root growth over time will be beneficial. This information can contribute to management decisions such as soil moisture sensor and probe placement for irrigation scheduling, dripper spacing, irrigation calculations etc. The aim with efficient drip irrigation is to minimize negative irrigation losses through evaporation and deep percolation (Hokam and Schmidhalter, 2008).

The water distribution patterns of conventional drippers in different soil types are well known. A lot of studies on water distribution patterns with drip irrigation are based on modelling and simulations as in field studies under orchard conditions are time consuming (Souza, Matsura and Testezlaf, 2015) and expensive (Skaggs *et al.*, 2004). The aim of this research is to study water distribution patterns in the soil profile, to visualize where the water is going when introducing the daily water requirement into the root zone continuously over the consumptive period of the crop, under citrus orchard conditions in relation to root growth distribution resulting from irrigation management via low flow drip irrigation.

Chapter2: Literature Review

2.1 Water consumption: The need for irrigation

Water account for one of the most important constraints to increasing food production in our hungry world (Postel, 1998). The thin balance between the unending demand for water by crops and the supply by sporadic precipitation makes crop production very difficult to a degree that modern agriculture in Arid and Semi - Arid regions must rely on irrigation to reduce the socio - economic pressure for increased crop production (Assouline *et al.*, 2006). For successful crop production, a water economy must be achieved, such that the demand made on it is balanced by the supply available to it, but **t**he problem is that the evaporative demand by the atmosphere is almost continuous (Hillel, 1998).

2.1.1 The demand: Evapotranspiration

The demand for water made on the plants is driven by the vapor pressure deficit between the quite dry atmosphere and the water saturated leaves, in other words the evaporative demand of the climate in which they grow (Vahrmeijer and Taylor, 2018; Lambers, 2008). The process of water vapor loss to the atmosphere is known as transpiration and is not a direct result of living processes in plants or an essential physiological function in itself (Hillel, 1998). During the process of transpiration, water is “pulled” upwards from the roots caused from sub-pressure (tension) as a result from a negative hydrostatic pressure in the leaves in reference to the atmospheric pressure caused from evaporation from the leaves (Lambers, 2008; Hillel, 1998). From the roots through the xylem to the stems and the leaves, a continuous pressure gradient is set up, driving the transpiration stream and this process proceeds continuously at a rate largely determined by the weather, as long as the plant’s ability to conduct water is sufficiently high and sufficient water is available to the roots in the soil (Lambers, 2008; Slatyer, 1957). It is known that plants draw quantities of water far in excess of their metabolic need from the soil and only a fraction is utilized in photosynthesis while most is lost through transpiration as vapour (often over 98%) (Hillel, 1998).

A linear relationship exists between transpiration and yield but flattens when transpiration reaches its climatic limit and beyond this point increasing production lies in identifying other environmental constraints (Hillel, 1998).

Experiencing stress, induced by high evaporative demand or low soil water content, plants are able to limit the rate of transpiration by "shutting" the stomates on the leaves (Schoeman, 2002). Rawlins and Raats (1975) concluded that crop yield is only maximal when water potential remains high throughout the life of the crop, but it is important to realize that regardless if soil is kept at a high moisture status, plants can experience water stress during periods of high transpiration due to increased water potential drop across resistances within them (Rawlins and Raats, 1975; Hillel, 1998).

In crop production, it is in the hand of the irrigator to ensure enough water is available at the roots to balance the demand for water to be consumed, allowing the crop to transpire to its fullest potential and to grow successfully. For irrigation purposes, the volume of water "consumed" in an orchard consists of evapotranspiration (ET) rather than transpiration alone (Rana, Katerji and De Lorenzi, 2005). It includes the amount of water transpired and the amount not taken up by the plants but evaporated directly from the soil surface. (Vahrmeijer and Taylor, 2018). In practice it is difficult to measure direct evaporation separately from transpiration so for convenience the two terms are joined, and ET is referred to as the "consumptive use" (Hillel, 1998).

ET is an important parameter for determining the irrigation requirement of crops (Fares and Alva; 1999) and have been studied intensively for the evergreen citrus under various climatic conditions and different irrigation regimes.

Yang *et al.* (2003) investigated seasonal variation in daily as well as hourly ET of greenhouse lysimeter grown eight-year-old 'Murcott' orange trees in Japan and found similar trends to Kadyampakeni *et al.,* (2014). Citrus tree water use follows a typical bell shape curve starting to increase at 06:00, with peak water usage from 11:00 to 15:00 and decreasing to a minimum at 20:00 (Kadyampakeni *et al.*, 2014; Yang *et al.*, 2003).

Irrigation requirements and water use of mature citrus trees have received a lot of attention but not the case for young trees (Fares and Alva, 1999). Fares and Alva (1999) calculated daily, monthly, and yearly ET of young non-bearing Hamlin orange citrus trees in field conditions by means of the water mass balance and reported daily ET values that followed a seasonal pattern of < 1 mm during winter to > 4 mm during summer. Irrigation was applied with 50 $l.h^{-1}$ sprinklers, one per tree. A conventional irrigation regime was followed and varied depending on available soil moisture. Daily ET of 3 year old Hamlin orange trees with Swingle citrumelo rootstock was recorded 1.3 mm in a 10 day period in November (Fares and Alva, 2000).

Actual evapotranspiration of mature drip irrigated Valancia orange trees grown in Uruguay reported 767 mm per year and a maximum monthly average of 3.3 mm per day (García Petillo and Castel, 2007). Irrigation was applied daily via 4 $L.^{-1}h$ pressure compensated emitters with one meter spacing, wetting a continuous strip of one meter width measured at 30 cm depth.

Morgan *et al.* (2005) estimated daily ET of mature citrus trees grown in a sandy soil in Florida and concluded mean daily ET that ranged from 4.6 $mm.day^{-1}$ in June to 1.3 $mm.day^{-1}$ in December and that soil water uptake rate and estimated evapotranspiration (ETc) was closely related to root length density. Kadyampakeni *et al.* (2014) recorded similar average daily water use of 4.02 ± 1.56 $mm.day^{-1}$, 135% of reference evapotranspiration (ET_o) in Spring and water use increased with drip, restricted micro-sprinkler and conventional treatments averaging 117, 109 and 85% of ET_o respectively in June. The greater water usage with drip and micro-sprinkler were attributed to daily frequent water application (Kadyampakeni *et al.*, 2014). ET followed a significant seasonal pattern in a study done by Yang *et al.* (2003) and average daily ET was 0.6 mm in the winter and increased to 4.4 mm in summer. Irrigation was applied when average soil moisture (0-120 cm depth) decreased to below 70% of field capacity.

When trees are young, larger irrigated surface area is exposed to direct sunlight due to smaller canopy size. A larger fraction of water consumed by the orchard would then be ascribed to direct evaporation from the soil surface but as the tree canopy increases less soil surface is exposed and a larger fraction of ET is water transpired (Vahrmeijer and Taylor, 2018). Generally, drip irrigation reduces evaporation as less of the soil surface is wetted (Communar and Friedman, 2010), but if the soil’s hydraulic conductivity is lower than the application rate, water ponds on the soil surface and increases evaporation loss (Skaggs, Trout and Rothfuss, 2010).

2.1.2 The supply: Irrigation scheduling

As a citrus orchard 'consumes' water, the challenge is to meet the demand ensuring enough water is available in terms of quantity and available in the active root zone for uptake when the trees need it. The fundamental principal of irrigation consists of introducing water into the part of the soil profile that serves as the root zone, for the subsequent use of a crop (Hillel, 1998). Drip irrigation has allowed more tight control over this process (Andreu, Hopmans and Schwankl, 1997).

Irrigation scheduling can simply be defined by two questions: when and how much water to apply (Hillel, 1998). Approaches to these two questions have changed a lot over the years with the soil's water holding capacity as the basis for irrigation scheduling. In the 1950's Veihmeyer and Hendrickson stated that water is equally available in a definable range between field capacity (an upper limit) and permanent wilting point (a lower limit) and any decrease in soil wetness, plant functions are thought to remain unaffected until the permanent wilting point is reached, at which plant activity diminishes abruptly (Novák and Havrila, 2006). However evidence was produced showing that water availability decreases with decreasing soil wetness (Kramer and Boyer, 1995) and plants can undergo severe stress when soil water content (SWC) is very low and the water uptake by the roots fails to meet the optimal evapotranspiration of the tree (Panigrahi and Srivastava, 2016). Attempts were made to divide the "available range" into "readily available water"(RAW) and "decreasingly available water", identifying a "critical point" of soil wetness between field capacity and wilting point as an additional criterion of soil water availability (Hillel, 1998; Novák and Havrila, 2006). From these fundamental ideas as the building blocks for irrigation, the 'reservoir' concept became the basis of irrigation management, allowing depletion of soil water until a desirable refill point is reached, depending on the specific crop's water demand and soil water holding capacity and refilled to field capacity (Lord and Jensen, 1975). This concept brings some clarity to when and how much to irrigate.

Actual transpiration decreases below the potential rate as water levels decrease, because the roots cannot extract water fast enough to satisfy climatic demand or the soil is incapable to supply water fast enough (Hillel, 1998; Novák and Havrila, 2006), either way the supply of water through the roots is insufficient to replace the loss of water from the leaves (Kaufmann and Hall, 1974). When this condition is reached depends on the weather, the plants and the soil and any attempt to disconnect one from the others and attribute it to soil conditions alone is ineffective and misleading (Hillel, 1998). Segal, Ben-gal and Shani (2006) explains that during water extraction, the water content in the area around the roots decreases and consequently the reduced hydraulic conductivity limits the rate of water uptake. This would then imply that the drier the soil-moisture regime, the lower the actual evapotranspiration. They mentioned that a shortage in water supply to the roots reduce the rate of transpiration and consequently reduces photosynthesis and yield.

Farming with perennial crops on sandy soil, frequent irrigation is self-evident due to low soil water holding capacity and the crop's water need is applied in smaller volumes stretched over the day (Phene and Beale, 1976). Intensively managed fertigation systems have become a tool to increase the efficiency of water and nutrient uptake, in which trees are fertigated daily or hourly (Melgar, Schumann and Syvertsen, 2010) and became popular in citrus production on sandy soils .

It is important to note that some of the principles commonly applied to conventional irrigation methods do not necessarily apply to drip irrigation. These principals include: the uneven distribution of water and minerals and its relationship to water availability, uneven distribution of roots and physiological effects of root restriction and the relationship between water availability and soil aeration (Bravdo and Proebsting, 1993). This may limit optimization of fruit production if not managed accordingly (Bravdo and Proebsting, 1993).

Through high frequency water application, it is possible to maintain a high water content within a portion of the root zone, minimizing drying and wetting fluctuation (Phene and Beale, 1976) and increasing the water flow and availability of nutrients to the roots (Segal, Ben-gal and Shani, 2006). The high concentration of roots known to develop under drip irrigation in the confined volume of irrigated soil have a large capacity to supply water to the above-ground growth (Bravdo and Proebsting, 1993). This is due to increased root surface area, a continuous maintenance of optimal soil water potential in at least part of the root system (as water uptake by roots is dominated by the effective root length, conductivity and the hydraulic gradient), a relatively low dependence on water movement in the soil and transfer of water between wet and dry roots (Bravdo and Proebsting, 1993).

Early results of an ACPS (advanced citrus production systems) trial done by Morgan *et al.* (2009) in Florida concluded that 10 pulses per day resulted in a wider water distribution pattern than one large pulse. Mature Hamlin trees established on a ridge showed increased fruit yields after 9 months of ACPS treatment prior to previous years and the intensive pulsed drip fertigation treatment had the highest yield compared to the two less intensive micro-sprinkler treatments (Schumann, Syvertsen and Morgan, 2009). The yield differences between treatments were ascribed to better fruit set rather than fruit size.

With Open hydroponic system (OHS) practices on citrus, pulsing or continuous fertigation is applied, but even under continuous irrigation, pulsing is also considered to better match water application rates to the crop's water requirement (Falivene, 2005). These practices reported to have two effects, maintaining the root zone water content near field capacity and the main core of the wetted zone is closer to the soil surface, resulting in less water moving past the root zone (Falivene, 2005).

Falivene (2005) mentioned that improvement in productivity is a general accepted principle in the citrus industry using drip irrigation instead of conventional sprinkler irrigation. In contrast to this, a fertigation frequency trial with drip and micro sprinkler irrigation conducted by Japie Kruger in 2000 concluded yield reduction from restricted root zone drip treatments and ascribed it to the inability to irrigate at "sufficiently frequent rates to meet the water needs of the trees" (Kruger *et al.*, 2000) emphasizing the necessity of suitable water scheduling practices for drip irrigation and restricted root zone (Falivene, 2005). The mixed results in fertigation and irrigation frequency research may highlight the effect of trial site in terms of soil, climate, plant material etc.

Hillel (1998) mentioned that with new irrigation systems allowing frequent irrigation the answers to when and how much to irrigate would be as frequently as is feasible economically and enough to meet the current evaporative demand and preventing salts building up in the root zone.

2.2 Continuous drip irrigation

A fundamental objective of drip irrigation is to lower the application rate close as possible to plant water uptake rate to improve irrigation efficiency (Phogat *et al.*, 2013). By lowering the application rate, the importance of physical properties of the soil is minimized, allowing efficient irrigation on previously unsuited soils (Rawlins and Raats, 1975).

The introduction of ultra-low flow discharge rate emitters (< 1 $l.h^{-1}$) to agriculture introduced certain irrigation approaches previously not possible. Rather than to pulse irrigate the daily water requirement, long daily irrigation cycles to meet the crop water demand is now a possibility. Applying water at such low rates and over long periods requires lower pressure, allowing greater hectares to be irrigated in one shift. Improved hydraulic application uniformity to ensure orchard uniformity in terms of vegetative growth and yields is an outcome, addressing a problem that may occur with pulse irrigation (C. Malan, personal communication).

With the development of lower discharge rate emitters (1, 0.7 and 0.4 L. h^{-1}) by Netafim, a further outcome is continuous drip irrigation, addressing many of the difficulties of managing drip irrigation in orchards established on low water holding capacity soils. According to C. Malan, continuous drip irrigation involves decreasing the application rate of the irrigation system to balance with the maximum daily water use over the total consumptive period of the crop. This is achieved by a flow rate of 2.5- 3.5 m^3.h. ha according to climatic crop water demand in one irrigation shift. The aim is to apply the water within 12- 14-hour period with ultra-low flow 0.7 or 0.4 L. h^{-1} drippers, preventing water movement beyond the root zone**.** The water consumption period of citrus can be up to 12 hours shown by the stem heat balance method and lysimeter studies done by Kadyampakeni *et al*. (2014) and Yang *et al*. (2003) respectively but varies in quantity over the total period.

During a short irrigation cycle when the irrigation time is a fraction of the consumptive period of the crop, water availability to the crop relies solely on the soil's ability to retain the water, storing it in soil pores, known as the soil water holding capacity (Datta and Stivers, 2017). Such an irrigation pattern is dominated by extraction following a brief period of infiltration but contrary, continuous irrigation is dominated by the process of infiltration, mitigating the importance of the soil physical properties such as soil water holding capacity, a previously highly emphasized characteristic for irrigable soils (Rawlins and Raats, 1975) . As the rate of water application by means of continuous irrigation remain constant over the crop's daily consumptive period the rate of crop water demand follows a typical bell shape curve (Yang *et al.*, 2003).

At an application rate close to the average water uptake rate, this would lead to an oversupply of water when the rate of crop water demand is low in the morning and late afternoon and under supply during peak water consumption. This would have implications on water content fluctuations of the wetted soil volumes known to form under drip irrigation as the wetted soil volume compensates for the under and over supply.

A shift from an irrigation pattern dominated by extraction to one dominated by infiltration would have implications on water movement and distribution in the soil, root zone conditions, root growth and distribution (Assouline *et al.*, 2006) and water use efficiency (Elabadin, Ibrahim and Omara, 2014; Assouline *et al.*, 2006) . It could also affect yield, fruit quality and -size as a change in soil water regime influence plant response (Assouline, 2002).

Some studies have reported that applying water at a low rate increased the average water content in the root zone and reduced water content fluctuation. Segal *et al.* (2006) stated that this would increase the availability of water and nutrients as the soil water potential around the active roots controls the rate of water and nutrient uptake (Assouline *et al.*, 2006). Falivene (2005) mentioned that continuous irrigation brings the core of the wetted soil volume closer to the soil surface. Some of the aims of continuous drip irrigation is to reduce under an over irrigation by more control over the irrigation depth and manage aeration in the root zone by the swelling and shrinking of the wetted soil volume as water is introduced to a portion of the root zone over a long period (C. Malan, personal communication). With drip irrigation the roots towards the outer parts in more exposed to air than those closer to the dripper as a gradient of water content result from 3-D water distribution under drip irrigation (Bravdo and Proebsting, 1993). A concern for managing aeration in the root zone would be when the wetted soil volumes overlap a lot or during heavy rain when the entire soil profile is wet and not just the irrigation 'pots' under the drippers. Traditionally adequate aeration was maintained in the root zone through extraction levels also known as the soil reservoir concept.

Not much research has been done on continuous drip irrigation, especially not on horticultural crops. Majority of the information on continuous drip irrigation and low application rates derived from studies on annual crops such as corn (Assouline, 2002)(Assouline *et al.*, 2002), tomatoes (Mofoke *et al.*, 2006) sunflowers 1 $L.h^{-1}$ (Segal, Ben-gal and Shani, 2006) and Bell Peppers 1.6 $L.h^{-1}$ (Assouline *et al.*, 2006) .

Drip irrigation has gained widespread recognition in citrus production, playing its role in Advanced citrus production system (ACPS) to battle citrus greening (Schumann, Syvertsen and Morgan, 2009; Morgan *et al.*, 2009), Open Hydroponic System (OHS) introduced by Professor Rafael Martinez Valero in 1990's (combining the concept of hydroponics with soil-based citrus production) implemented by farmers in Australia, Spain, South Africa, Argentina Chile, California and Morocco (Falivene *et al.*, 2005) and Intensive Fertigation Practices (IFP) (Srivastava, 2015). These practices al aims to maintain favourable root zone conditions in terms of water content and water- and nutrient availability on soil previously considered as unsuited, by constricting the root zone using low application rate drippers and reduced amount of drippers per tree (Schumann, Syvertsen and Morgan, 2009; Sluggett, Biswas and Hutson, 2016).

With low flow drip irrigation sensitive crop management can be achieved as crop water requirements are applied over the consumptive period of the crop (C. Malan, personal communication) allowing for the nutrient medium to create the environment for root growth rather than the soil (Schoeman, 2002). Continuous drip irrigation can be seen as a tool, similar to OHS and daily daylight fertigation, in growing conditions with low quality soils and poor water quality (Schoeman, 2002).

2.3 Soil water dynamics

Sokalska *et al.* (2009) stated that a key to increase the efficiency of drip irrigation, the shape of the wetted soil volume should be adjusted to the main root mass distribution of the irrigated plants .The wetted soil volume created due to three dimensional water distribution under drip irrigation (Cote et al., 2003; Schwartzman and Zur,1987; Elmaloglou and Diamantopoulos, 2007) and with it the spatial distribution of soil water content and solute concentrations (Assouline, 2002) are dependent on various interrelated factors including the soil hydraulic properties, emitter discharge rate, frequency of irrigation, volume of water applied per irrigation, total amount of water in the soil as well as root distribution patterns and water uptake rates (Schwartzman and Zur, 1987; Hopmans *et al*., 2005; Assouline, 2002).

Hokam, El-Hendawy and Schmidhalter (2008) mentioned that one of the most important factors that effects the soil water regime and hence the water and fertilization use efficiency and crop yield in drip irrigation scheduling is irrigation frequency, although applying the same quantity of water. Lowering emitter discharge to a rate closer to plant water uptake rate would imply changes to irrigation efficiency (Assouline, 2002), soil water distribution patterns and water fluctuation during seasons of crop growth as application rate influence the soil water regime (Schwartzman and Zur, 1987; Hopmans *et al*., 2005) .

Now that irrigation systems can apply the same quantity of water over a longer period (continuously with low discharge), synchronized with the period of active water uptake, the importance of studying water distribution and plant response is emphasized, to manage and adapt irrigation scheduling to ultimately optimize production and increase irrigation efficiency. How would application rate close to the water uptake rate by citrus trees affect water distribution and fluctuation over time: hourly, daily, monthly, and seasonally? The relationship between discharge rates, soil properties and the soil water regime are well documented for conventional drip irrigation (≥ 2 L.h^{-1}) (Bresler and Yasutomi, 1990) (Assouline, 2002,) but not the case for continuous irrigation with low discharge rates (Assouline *et al.*, 2006).

2.3.1 Application rate and water distribution

The wetted soil volume created under drip irrigation during water application is generally characterized by two zones : A saturated zone close to the emitter and a zone of decreasing water content towards the wetting front, creating a gradient in water content (Assouline, 2002) towards the periphery of the wetted soil volume (Bouksila, Slama and Berndtsson, 2005). Various studies on application rate shows a change in water content gradient toward the wetting front with change in emitter discharge (Bar-Yosef, 1999; Assouline,2002)

Assouline (2002) came to the same conclusion in an experiment comparing 8 and 2 L. h^{-1} drippers (conventional drip) and 0.25 L. h^{-1} (micro-drip) and only observed a saturated zone in the 8 $L.h^{-1}$ treatment and least extreme water content gradients for micro-drip in both vertical and horizontal directions. Micro drip also resulted in the smallest wetted soil volume.

The ponding zone developing around the emitter is strongly related to the application rate and soil properties. Thus, the unique relationship between the water content distribution in the wetted soil volume and the amount of water infiltrated is therefore not valid for drip irrigation as for one dimensional water infiltration such as flood or sprinkler irrigation (Assouline, 2002)

Increasing application rate generally result in increased diameter of the wetted soil volume and a decrease in depth (Assouline, 2002;Bar-Yosef, 1999; Fan *et al.*, 2018). Bravdo and Proebsting (1993) reported a similar trend in the relationship between distribution and application rate namely that horizontal water distribution increases with emission rate. A pronounced increase in the wetted soil volume compared to decrease in wetted depth is observed when doubling the emitter discharge rate and the trend is expressed more in heavier soils (Schwartzman and Zur, 1987).

Horizontal water movement is driven by the capillary forces of the soil, primarily determined by the soil hydraulic properties and water content (Skaggs, Trout and Rothfuss, 2010). Skaggs, Trout and Rothfuss (2010) also mentioned that some irrigation guidelines indicate that an increased horizontal/vertical ratio of the wetted soil volume will be the result of increasing the emitter discharge rate. Water tend to pond on the surface under emitters with high application rates and causes water to spread over the surface (Skaggs, Trout and Rothfuss, 2010) increasing surface evaporation and compromising control of the water distribution (Elabadin *et al*., 2014; Skaggs *et al*., 2010). Assouline (2002) recorded no saturated zone with micro drip irrigation (0.25 $L.h^{-1}$).

Skaggs, Trout and Rothfuss (2010) and Cote *et al.* (2003) recorded trends with drip discharge, indicating that a decrease in the discharge rate (increased irrigation time) slightly increased horizontal spreading of the wetted volume but it is unsure if the increase in wetting was great enough to be of practical significance due to observations made at the end of simulated water application and not after redistribution occurred. The geometry of the wetted soil volume at the end of an irrigation event is dependent upon emitter discharge, soil type and the total amount of water applied (Schwartzman and Zur, 1987).

A study done by (Rui *et al.*, 2012) looked at the dynamics of surface wetted radius and vertical depth under different discharge rates; 0.5, 1.2, 1.5, 1.7, 1.9 and 3.9 $L.h^{-1}$. A trend resulted of higher application rates being associated with a larger surface wetted radius (Rui *et al.*, 2012). High emitter flow corresponded with large vertical wetted depth and is a growing tendency with increase in irrigation time (Rui *et al.*, 2012). Li, Zhang and Ren (2003) reported that water moves faster horizontally and vertically with an increase in application rate however for a given volume applied a larger discharge rate led to a greater radius to depth ratio. Thus, for a given volume applied, more water distributes in the vertical direction by decreasing the application rate as in low flow drip

Contrary, simulations for a sandy loam soil showed slight increase in the relative horizontal to vertical spread associated with low application rates (achieved by low emitter discharge or pulsing) and low antecedent soil water, but the small increases were not due to flow phenomena but primarily to longer irrigation times (Skaggs, Trout and Rothfuss, 2010). General trends were observed in simulations: decreasing the application rate and antecedent soil water content respectively increased relative horizontal spreading, but the effects of low application rate, antecedent water content and pulsing was not of practical significance (Skaggs, Trout and Rothfuss, 2010). An increase in the soil water content will increase wetted depth considerably more than width and this trend is more pronounced in light textured soils (Schwartzman and Zur, 1987). This phenomena is attributed to less pore space being available to hold the applied water (Skaggs, Trout and Rothfuss, 2010).

Schumann, Syvertsen and Morgan (2009) did research on ACPS, comparing daily water and nutrient application (open hydroponics), via 0,53 gph pressure compensating (2 L/h) emitters with standard fertilizer practice. The OHS system aimed to manage soil water content of the 0-4-inch depth (10 cm) near field capacity through pulse irrigation (10 times per day) or a single large pulse per day (continuous irrigation). They described the horizontal water spreading of no more than 6 to 8 inches (~15-20 cm) from drip emitters, but a slightly wider pattern resulted from pulse irrigation (Schumann, Syvertsen and Morgan, 2009). The duration of the single large pulse and pulses were not indicated as well as the extent of the vertical water movement under these conditions (Schumann, Syvertsen and Morgan, 2009). Similar water regimes created and observed under continual low application rates can be obtained by pulsing with conventional drip emitters(>2 $L.h^{-1}$) (Assouline, 2002; Phogat *et al.*, 2013)

Assouline (2002) concluded how micro drip affects the water distribution in the root zone observing an increased drying in the 60 -90 cm depth compared to conventional drip irrigation and reported the possibility of improved yield and reduced drainage flux in a maize trial. The main difference seems to be close to the drip line between the high, standard, and low application rates, expressed in a modelled 2-D visualization (Assouline, 2002).

Skaggs *et al*. (2010) concluded that in practise it is the texture (hydraulic properties) of the soil and the antecedent soil water content that will determine the soil wetting pattern from drip application for a given volume of water and will not be significantly impacted by pulsing or discharge rate. Michelakis, Vougioucalou and Clapaki (1993) stated that the extent to which water distributed under an emitter is a function of the discharge rate and spacing of drippers but is mainly dependant on the soil texture and the volume of water applied. Fan *et al*. (2018) concluded that both the wetted soil volume and the wetting depth have a positive correlation with the initial water content. The higher the initial soil water content, the greater the soil water conductivity and consequently the volume of water to fill the soil pores is reduced, accelerating the wetting front movement (Fan *et al.*, 2018).

2.3.2 Change in soil water content

Closely monitoring irrigation by observing graphs depicting the soil water content changes over time constructed from probe readings has become a helpful tool and general practise in agriculture . Drip irrigation, however bring challenges in monitoring soil water content due to partial soil wetting (Phogat *et al.*, 2012), 3-D water distribution (Assouline, 2002), gradients in water content and the doubting significance of averages or single values representing the SWC (Bravdo and Proebsting, 1993). From literature we know that the soil water regime can change with a change in discharge rate (Assouline, 2002; Assouline *et al.*,

2006) and will reflect in the slow or rapid increase of water content over time at different soil depths (Assouline, 2002; Assouline *et al.*, 2002; Assouline *et al.*, 2006; Segal, Ben-gal and Shani, 2006).

Observing changes in soil water content over time can transfer valuable information, portraying the relationship between irrigation (application rate), water infiltration, plant water uptake patterns, soil behaviour and climatic influence. Observed changes may also indicate the extent of processes like water redistribution and drainage depending on where soil moisture sensors are placed (Zotarelli, Dukes and Morgan, 2019).

Under relatively high application rates, the process of infiltration is a small fraction of the uptake period and a rapid increase in water content in the active root zone is observed, reaching field capacity and usually into saturation. When water application ceases, the rate of decline in water content may indicate the extent of drainage, water uptake or redistribution, depending on time after the irrigation event or the time of day. Lowering the application rate would imply a rise in the ratio of infiltration time relative to extraction. Under low continuous application, infiltration and water uptake would occur concurrently, at a somewhat similar rate. The rise in SWC is expected to be a steady incline as lower volumes of water are introduced to the soil over time while water is being consumed and the representing graph is expected to be one of gradual change in soil water content, a characteristic pattern representing corresponding plant behaviour under the resulting water regime (Assouline, 2002).

Assouline (2002) recorded water content changes in a corn trial and simulation experiments for three different drip discharge rates: 8, 2 and 0.25 L.h^{-1} (micro-drip) . At the end of the corn trial, the relative water content of the 0.25 L. h^{-1} treatment was recorded to be the highest in the upper 30 cm and lowest in the 60 to 90 cm depth in the soil profile. The author mentioned that this could be an indication of different water uptake patterns and root structure resulting from low application rates compared to conventional drip. The researcher also found that simulated dynamics of water content changes at different depths for the three application rates showed that micro-drip had the least variable water content over a diurnal period and when compared at solar noon, when water demand is the highest, micro-drip was the wettest in the upper 20cm soil layer. Assouline (2002) recorded longer delay before water content rises and rising rate was shallower as application rate decreased. The author mentioned that for the two conventional emitters, maximum SWC preceded solar noon and redistribution was taking place for hours while wetting had not ended for the low application rate. Part of the daytime and all night-time, micro drip had the highest water content at the 20cm depth and highest water content at the end of the irrigation cycle (Assouline, 2002).

Segal (2006) recorded steadier water content at higher levels of soil water content (0.22 $cm^3.cm^{-3}$) for continuous and eight pulses per day with 1 L. h^{-1} discharge rate compared to once every two days and eight days. The author found that average water content was 0.23, 0.21, 0.19 and 0.15 $cm^3.cm^{-3}$ respectively and higher frequency irrigation corresponded with higher yields. ET also corelated directly to the biomass of the sunflower plant between treatments and a linear relationship was found between relative yield and relative ET (Segal, Ben-gal and Shani, 2006).

Cohen *et al*. (2006) stated that continuous low flow irrigation or frequent pulses per day in a bell pepper case study could lead to higher water and nutrient availability in the active root zone compared to a traditional irrigation regime of one irrigation event a day. Research also found that it reflected in less fluctuation in the soil water content and high soil water content in the active root zone during peak water demand.

2.4 Citrus root growth and distribution

As the hidden part of the plant, the root system plays an important role in water extraction, nutrient absorption, hormone synthesis and ground anchorage (Spiegel - Roy and Goldschmidt, 1996). Knowing its importance and how it is affected by change in irrigation regime is critical in agriculture, especially for increasing the efficiency of cultural practices such as irrigation and fertilization (Castle,1994). A small amount of information pertaining root growth of horticultural crops are available but most of our knowledge of roots are from monocotyledons, characterized by rapid growth, relatively shallow root systems and short life cycles (Castle, 1978).

2.4.1 Root Structure (basic morphology)

As with most fruit crops the evergreen *Citrus* root system is a separate biological entity, which can be modified through root stock selection (Castle,1994).
Like most other dicots, citrus trees are tap-rooted as the radicle appears first at germination and grows rapidly downwards, however can be often lost during nursery practises and transplanting into orchards (Spiegel - Roy and Goldschmidt, 1996).

Studies by Castle (1978) and Castle and Krezdorn (1979) have shown that a typical root system of a citrus tree has a bi-morphic nature that entails a network of lateral roots not far from the surface that serve as a framework for fibrous roots forming a dense mat . Smaller laterals and fibrous roots emerge from the crown in a deeper second layer with a more -or-less vertical orientation (Spiegel - Roy and Goldschmidt, 1996). In deep sandy soils these roots can account partially for roots observed at depths greater than 0.5 m to 1 m (Castle, 1978; Ford, 1954). A framework of pioneer roots establishes from the subdivision of these larger lateral roots, from which smaller ones arise and along these smaller roots, fibrous or clusters of fine roots develop (Spiegel - Roy and Goldschmidt, 1996).

One should not assume that citrus root structure is a stable characteristic but it can change with factors such as soil physical or chemical differences, cultivar or soil organisms (Castle, 1978)

2.4.2 Root Growth

Root growth embodies elongation and increase in diameter but has generally been used to describe the elongation of fibrous roots which often do not undergo secondary growth (Castle, 1978)
Citrus roots grow periodically with 2 to 3 cycles annually (Bevington and Castle, 1985) but some growth takes place uninterruptedly varying in intensity considerably as long as soil moisture, temperature and aeration are adequate (Spiegel - Roy and Goldschmidt, 1996). Roots of established citrus trees grow in alternating growth flushes with the shoots (Syvertsen, Smith and Allen, 1981). The growth period may overlap in flushes as the one does not eliminate the other but cycles are observed as one major organ competes with the other for the available food supply, resulting in an temporarily unbalanced plant assimilate distribution supporting the most competitive growing organ or strongest sink (Castle, 1978).

Bevington and Castle (1985) described the annual root growth as continuous, interrupted periodically by cycles of shoot growth suggesting an interrelationship between root and shoot growth. Thus, root growth is the greatest when trees are not flushing.

Young citrus tree root growth proceeds vigorously until the tree begins to bear fruit or the volume of soil available for root growth becomes fully exploited. According to root mortality is substantial in nonwoody species but minimal in citrus (Glenn, 2000).

Root distribution and growth, that involves proliferation in the soil regions where they are present and extension into new regions, are affected by a lot of factors additional to soil moisture content and nutrients, including temperature, aeration, mechanical resistance, the possible presence of toxic substances, and whether the primary roots prefer to grow vertically downward (Hillel, 1998).

Bevington and Castle (1985) did an intense study on the annual root growth pattern in relation to soil water content, soil temperature and shoot growth and reported the root growth of Carrizo citrange in terms of number of root extensions and root growth in $cm.day^{-1}$. They reported that root growth commences at 13°C but that growth was relatively minor below 22°C. Castle (1978) reported that root growth is limited at soil temperature above 36°C and optimal near 26°C. 'Carizzo' citrange root growth rate increased from 1.6 to 6.5 $mm.day^{-1}$ early in Spring (Bevington and Castle, 1985).

Soil water potentials less than – 0.05 MPa is found to limit root growth and when soil temperature is adequate, root growth is controlled readily by water deficits regardless the state of shoot growth (Bevington and Castle, 1985; Pijl, 2001). Increase in water content lowers soil strength, allowing root growth. Root systems able to sustain above ground growth are likely to be formed under drip irrigation as long as high water availability with sufficient nutrient concentrations and appropriate aeration prevails (Bravdo and Proebsting, 1993).

2.4.3 Root Function

Most of the information on citrus root function derived from studies directed toward rootstock differences and their effects on salt tolerance and on leaf and root nutrient content (Castle, 1978).

Root structure, function and growth can be considered and studied separately but are not independent entities (Castle, 1978). Considerable evidence connects root architecture with water and nutrient acquisition efficiency (Dupuy, Gregory and Bengough, 2010). In general the root system architecture is important for the plant to access soil resources and the root system structure determines the volume of soil accessible to crop plants as well as the pathway for water and solute uptake (Morgan and Obreza, 2007).

Considering the general root structure explained above, water and applied nutrients are rapidly absorbed from the upper soil layers by the mass of dense shallow fibrous roots (Philip, 1997)

The deeper second layer serves as a reserve, responsible for the uptake of nutrients not absorbed by the shallower roots and preventing extreme drought stress (Spiegel - Roy and Goldschmidt, 1996). Studies on rootstock and soil depth on root efficiency reported that deeper roots are generally more efficient in water uptake (Castle, 1978).

2.5 Root Studies

Irrigation is known as the process of introducing water into the part of the soil profile that serves as the root zone (Hillel, 1998). Knowing where the major tree root zone is located and in what concentration serves several practical purposes especially to increase the efficiency of cultural practices such as irrigation and fertilization (Castle, 1978). To adapt irrigation practises accordingly, roots studies must be performed to establish root depth and any compaction layers influencing irrigation regime (Michelakis, Vougioucalou and Clapaki, 1993).

2.5.1 Profile wall method

A lot of studies have been done on the relationship between root growth and different irrigation regimes and techniques and the profile wall method has been a popular and effective way to quantify the resulting root distribution. The profile wall method entails digging a trench close to tree or between adjacent trees up to a desired depth to study the site-specific root distribution in the soil profile (Stofberg, 2018).

By means of the profile wall method Sokalska (2009) studied the spatial root distribution of mature apple trees under different irrigation regimes via drip. Pijl (2001) quantified the root growth of 4-year-old Nules Clementine citrus trees (Troyer root stock) under micro irrigation, conventional drip fertigation and daily drip fertigation (1.6 L.h) using the profile wall method. Jorge *et al.* (2005) estimated the root area of grapevines using the profile wall method in combination with digital image analysis under drip (3.7 L.h) and micro sprinkler irrigation. Root studies are limited in a way of only being able to study a part of the root system at once and leaves some questions if it is a pioneer root, the main or branch root in a cluster that are observed (Castle, 1978). Despite the uncertainty, a general picture of citrus root growth can be formed, and the profile wall method is able to portray the general root distribution within the soil profile in relation to irrigation, fertilization, soil properties, phenology etc.

2.5.2 Auger samples: Fibrous root distribution

As nutrient and water uptake is a function of fibrous root length density (FRLD) and water content (Morgan, Obreza and Scholberg, 2007; Raats, 2007), more water and nutrients will be available to the crop with an increase in length of fibrous roots within the root system (Morgan, Obreza and Scholberg, 2007; Dalal, Bons and Baloda, 2014).

Understanding the growth pattern and distribution of fibrous citrus roots enables proper water and fertilizer placement to increase water and nutrient use efficiency and reduce leaching below the root zone. Though fibrous root distribution may vary with rootstock, soil depth, etc. an indication of the fibrous root distribution at a given point in space can be obtained by a representative volume typically used in root system measurements. This can range between 100 cm^3 and 200 cm^3, above which stochastic effects become negligible and various measurements such as mass, specific area, volume fractions or length density can represent the state of the root system (Dupuy, Gregory and Bengough, 2010). Auger samples have been included in various root data collection trials.

Castle and Krezdorn (1979) investigated the relationship between distribution and quantity of feeder roots of 11 different rootstocks and tree height and leaf mineral status, taking auger samples at the drip line. The data obtained showed that mean tree height, total feeder root weight and rooting depth varied with rootstock.

Auger root samples of mature 14 year old Hamlin orange trees on Carrizo citrange and Swingle citrumelo rootstock indicated that fibrous root length density, as a function of soil depth from the surface and distance from the tree trunk, distinctly differed between rootstocks (Morgan, Obreza and Scholberg, 2007). Trees on Swingle citrumelo rootstock had significantly greater FRLD near the soil surface than trees on ‘Carizzo’ citrange rootstock (Morgan, Obreza and Scholberg, 2007). Samples were taken at 15 cm increments with a 7.6 cm diameter bucket auger.

Feeder root dry weight density (FRDWD) differed significantly at different depths and radial distances between sweet orange trees on Cleoptera, Rough lemon and Troyer rootstocks. FRDWD was almost the same in depths 0-15 and 15-30 cm , with approximately 70 % of total feeder roots in the top 30 cm in all rootstocks (Dalal, Bons and Baloda, 2014). Samples were taken at 15 cm depth increments at specific radial distances from the tree trunk.

Castle also investigated fibrous root distribution, expressed as fibrous root weight (FRW) of ‘Pineapple’ orange trees on rough lemon rootstock at different tree spacings, and concluded that root weight density was greater for higher density plantings, suggesting overlapping of adjacent root systems (Castle, 1990). Not a lot of studies have been done on the effect of irrigation on citrus fibrous root length density distribution, especially under low application rate drip irrigation. Kadyampakeni *et al*. (2014) did a study on the effect of irrigation pattern and timing on root density of young citrus trees. Higher RLD were recorded for intensive irrigation and fertigation practices in irrigated zones compared with conventional applications. In the research root samples were collected only up to 30 cm in depth (in 15 cm increments), where most roots of young citrus trees (< 3 years) are concentrated.

2.6 Influence of daily drip irrigation on root distribution

There has always been a question what effect frequency and duration of irrigation has on deep rooted crops (Bevington and Castle, 1985). According to Castle and co-workers, the effect of irrigation is expected not to be drastic except in areas where rainfall is sporadic, irrigation is applied by low volume under the tree systems and in young trees.

The introduction of drip irrigation and fertilization techniques changed the root system structure dramatically (Spiegel - Roy and Goldschmidt, 1996). It is well known from literature that daily drip limits the root system to a restricted volume of soil that creates physiological root restriction effects similar to what can be observed in container grown trees (Bravdo and Proebsting, 1993). Root growth is expected to increase in the wetted regions when only a portion of the root zone is wetted (Glenn, 2000). According to Glenn (2000) root growth slows in dryer regions of soil due to reduced carbon partitioning. It is found that when the soil temperature is suiting, root growth may be regulated by irrigation timing (Bevington and Castle, 1985).

Kadyampakeni *et al.* (2014) conducted a study to investigate the effect of intensive fertigation management on RLD and water distribution patterns associated with young Hamlin orange trees on swingle rootstock. After 2 years they recorded that RLD was greatest in 0-15 cm depth in all treatments (conventional, daily restricted micro sprinkler and daily drip). In the first year of the study roots samples showed that 64 to 82% of the fibrous roots were concentrated in irrigated zones of both restricted micro sprinkler and drip irrigation. In this research, 18 to 36% occurred in the non-irrigated zones. High summer rainfall also caused greater RLD in non-irrigated zones in 15-30 cm depth close to the dripper and irrigated zone of restricted micro sprinkler than irrigated zones of conventional irrigation.

Pijl, (2001) investigated the water distribution and resulting root distribution under 1.6 l.h drippers, one dripper per tree close to the tree trunk. The results of this are that the highest root concentration was in the vicinity of the dripper. In an area of 60 cm vertical depth and 20cm horizontally which represented 19% of the profile wall area, 83% of the roots were found. This correlated with the extend of the water distribution recorded with EnviroScan capacitance probes.

The researcher also studied the root distribution under daily drip fertigation at two soil types, sandy and silt loam soil, applied according to water content measured with Enviro-Scan capacitance probes. The sandy soil was irrigated in two pulses and silt loam soil in one pulse (continuous). In the sandy soil, root distribution parallel and perpendicular to the drip line differed significantly. Parallel to the drip line 54% of the roots were found in an area of 40 cm in width by 60 cm in depth, with the emitter located in the middle. On the outside of this area, up to 60 cm from the dripper on both sides, 46% of the roots were located. The researcher also found that perpendicular to the drip line, 67% and 33% of the roots were in the same areas respectively.

Larger number of roots were observed under intensive drip irrigation of ‘Gloster’ apple trees on M26 rootstock compared to economical drip irrigation, with a strong trend of root accumulation near the emitter to a depth of about 40cm (Sokalska, 2009). The researchers found that the root distribution was uneven including fine (< 1 mm) and coarser roots (1-3 mm) with most of the roots in the wetted area close to the soil surface and on the other side of the trunk with no emitter, significantly larger number of roots developed, penetrating deeper soil layers.

Studies in deep sandy soils of central Florida showed that tree size and yield are related to fibrous root dry weight density or distribution (Morgan, Obreza and Scholberg, 2007) and irrigation affects the number of fine roots (<1 mm) which in turn influences the yield (Sokalska, 2009).

The root distribution is a result of the corresponding soil water regime associated with the irrigation frequency and discharge rates (Assouline, 2002; Cohen *et al.*, 2006). This puts emphasis on studying root distribution with water distribution in the soil profile as they influence each other. Most of the results derives from higher discharge conventional drippers and very littlle information is available on citrus root growth associated with low discharge continuous drip irrigation .

In summary, the highly restricted root zone with high density fibrous roots that generally develops in the confined volume of irrigated soil have a tremendous capacity to supply water and nutrients to above ground growth due to continuous provision of optimal soil water potential to part of the root system, increased root surface area and relatively low dependence on water movement in the soil (Bravdo and Proebsting, 1993).

2.7 Root water uptake in relation to soil water availability

In drip irrigation, the emitter discharge rate and frequency are factors which determine the variation in soil water potential around the emitter and consequently the root distribution and the plant water uptake patterns (Assouline, 2002; Cohen *et al.*, 2006). Irrigating only a portion of the root zone as with drip irrigation, root density is expected to increase in the wetted areas compared to dry areas in the soil profile (Glenn, 2000; Falivene, 2005) and water uptake by roots in the wetted areas increases relative to the amount taken up when the entire root system is wetted (Glenn, 2000). Zones with highest root density generally contributes to higher water uptake as a strong correlation exists between water uptake and root density (Kadyampakeni *et al.*, 2014).

Panigrahi and Srivastava (2016) observed in a water management study on 12-year-old Nagpur mandarin citrus trees how the mean soil water fluctuation between two consecutive measurements under full irrigation (FI) (2.0–6.5 mm) was higher than under deficit irrigation (DI) treatments (0.3–3.0 mm) and ascribed the difference to higher evapotranspiration rate of trees under increased soil water availability under FI compared to DI.

Regions of maximum water uptake shift to locations where soil water is most easily available within the root zone as the wetted soil volumes become depleted after irrigation ceases (Andreu, Hopmans and Schwankl, 1997). Thus, as Assouline (2002) and Cohen et al (2006) mentioned, the resulting soil water regime will determine patterns of root water uptake. As the evaporative demand does not cease, a larger soil volume is being exploited to compensate for the decrease in water uptake rate in the active root zone to satisfy the evaporative demand (Andreu, Hopmans and Schwankl, 1997). If water application ceases for prolonged periods, the whole rooting zone can become depleted and the rate of root water uptake and daily ET decrease (Hillel, 1998). Change in citrus tree's root water uptake pattern can be observed from season to season as well. Yang *et al.* (2003) recorded that in the summer, orange trees grown in greenhouse lysimeters had maximum water uptake in 30–60 cm depth and depletion of soil water was observed in the 0–120 cm depth of the profile, but during the winter season, water depletion occurred only from 0–30 cm depth of the soil profile.

Similar or greater water use than conventional was observed for ACPS (frequent irrigation), despite irrigating a limited rooting area, due to increased soil water availability and root length density in the irrigated zone (Kadyampakeni *et al.*, 2014).

Morgan *et al.* (2005) found the best correlation between soil water content and daily water use in the soil volume that has the highest root length density. Maximum water uptake per unit root length occurred at field capacity (1.3 $mm^3. mm^{-1}$) and uptake rate decreased rapidly to 0.5 $mm^3. mm^{-1}. d^{-1}$ as the soil water content decreased to 50% available soil water depletion (ASWD) (Morgan *et al.*, 2005).

2.8 Crop response to Irrigation management

Water has a central role of a major metabolic agent in the life of plants (Hillel, 1998). The evergreen citrus is a high-water demanding crop varying with season and climate (Mostert, 1999). Citrus trees respond rapidly to water availability shown by various deficit irrigation studies (Chartzoulakis, Michelakis and Stefanoudaki, 1999; Domingo *et al.*, 1996; García-Tejero *et al.*, 2010; Shirgure and Srivastava, 2013) and the response to water stress is mainly reflected in yield and fruit quality (García-Tejero *et al.*, 2010) due to sensitivity during the phenological stages of flowering and fruit growth stages (García-Tejero *et al.*, 2010; Mostert, 1999; Shirgure and Srivastava, 2013). Mostert (1999) found that water stress during the stage of cell division has an irreversible effect on fruit quality. The greatest detrimental effect on fruit size and yield is due to water stress in the rapid fruit development stage (Hoffman, 2006). When water savings is up to 1000 $m^3. ha^{-1}$, effects may be particularly severe (Tejero *et al.*, 2011; García-Tejero *et al.*, 2010).

Trees irrigated with 140% ET yielded 43% more compared to 50, 80 and 110% which did not differ significantly from each other in a drip irrigation ($4L.h^{-1}$ discharge) trial on five-year old Clementine trees (Castel, 1994). Water extraction level of 20% plant available water resulted in average higher yield, fruit weight, total soluble solid (TSS) and juice % compared to 10 , 30 and 40% extraction levels under drip irrigation (Shirgure, Srivastava and Singh, 2001). Promising results were found in South Africa showing increased yield of Clementine and Valencia oranges of 25% and 19% respectively under an OH system compared to micro-irrigation with broadcast fertilizer application (Srivastava, 2015). Higher yields of drip irrigated Nagpur mandarins were recorded in a mulch experiment ascribed to higher conserved soil moisture status at 15 and 30 cm depth (Shirgure *et al.*, 2003). Highest juice % (49.86), TSS (10.4°B (Brix)) and fruit weight were associated with treatments that maintained highest soil moisture status at the 15 and 30 cm depth, although differences in TSS were not significant. Irrigation scheduling at SWP levels of -0.01 MPa (field capacity) and -0.05 MPa via drip indicated no significant difference in yield, fruit number and -weight, juice, TSS or acidity % of 'Bonanza' orange trees (Chartzoulakis, Michelakis and Stefanoudaki, 1999). The researchers found significant lower yield and higher TSS% at -1.5 MPa SWP based scheduling as well as trends of lower juice % and fruit weight and higher acidity.

Increased fruit size and yield in sprinkler irrigated grapefruit trees resulted from setting the soil refill point to 10-15 kPa compared to 35-34 kPa in an irrigation frequency trial (Falivene, 2005). No differences in growth, yield or fruit size of young trees were observed between daily, weekly and monthly fertigated treatments but higher leaf N was recorded for daily treatments (Syvertsen and Jifon, 2001).

Prinsloo (2007) reported that daily daylight irrigation or continuous irrigation reduce sugar content in citrus due to the amount of water applied that dilutes the sugar that accumulates in fruit. Citrus rootstocks varying in their vigour of growth also influence sugar accumulation in fruit (Barry, Castle and Davies, 2004;Prinsloo, 2007).

Chapter 3: Materials and Methods

3.1 Trial site

3.1.1 Site selection

The study was conducted on a commercial farm (Denau farming) near Worcester in the Western Cape (South-Africa), situated in the mouth of the Hex River valley leading to de Doorns (Figure 3.1). Located next to the Hex River (33°35'52.21"S , 19°30'51.90"E), the area can be considered as an old riverbed characterised by sandy soils and river rocks. This area is known for table grape, wine grape and citrus production. Elevated 291 m above sea level surrounded by mountains, average maximum temperatures of 31°C are reached from December to February and minimum average temperatures of below 4°C are recorded in July (Figure 3.2). The Western Cape has a Mediterranean climate and receives rain during the winter. Highest rainfall in the de Doorns area are usually during June and July with long term means of 75 mm and 55 mm respectively and lowest in Feb (10.4 mm). Annual rainfall is expected to be around 350 mm (total of average total monthly rainfall, 2004-2016) (ARC).

Figure 3.1. Location of trial site near Worcester - Western Cape, South Africa.

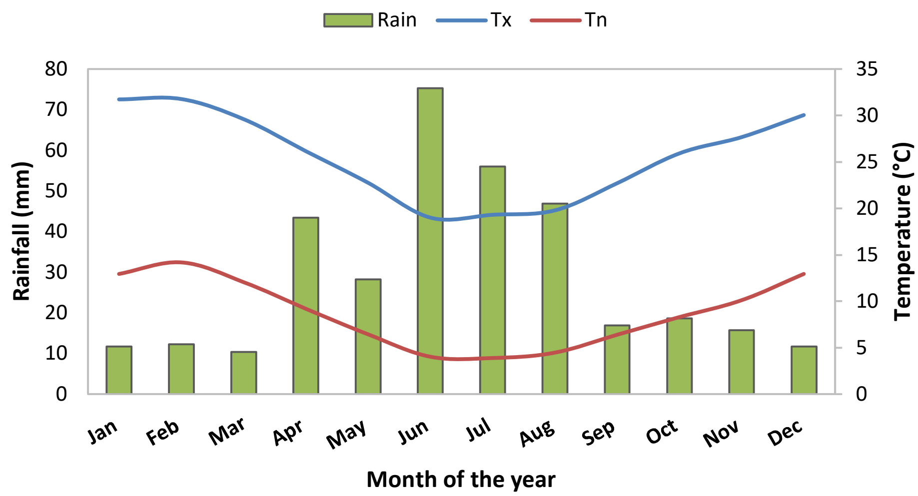

Figure 3.2 . Long term rain, maximum and minimum temperature averages for the Hex Valley region (2004 -2019) (Agricultural Research Counsel (ARC))

3.1.2 Cultivar and rootstock

The citrus cultivar under trial in the experimental orchard is 'Nadorcott' mandarin (*Citrus reticulata* Blanco). 'Nadorcott' mandarin is a mid to late maturing cultivar and known for highly productive yields even for young trees (Feyrer, 1998). Fruit are easy-peeling, has excellent aroma and flavour with a superior rind and juice colour compared to 'Murcott' (Feyrer, 1998). The cultivar is grafted onto Carrizo citrange (*Citrus sinensis* × *Poncirus trifoliata)* generally a vigorous rootstock and known to be medium to high salt sensitive (Moya *et al.*, 2003).

3.2 Experimental orchard

3.2.1 Orchard selection

The experimental orchard selected is part of a 'Nadorcott' mandarin orchard, established in 2016 (Figure 3.3). The orchard is established under white net and produced its first harvest in 2019. The orchard is situated on a slight slope, descending in the east west direction toward the Hex River with tree rows planted in the north-south direction. The orchard can be described as a medium density orchard with a spacing of 2.5 m x 5 m (Figure 3.4) and planting density of 800 trees.ha^{-1}, established on ridges as depicted in Figure 3.5.

For the purpose of the trial 15 rows of 47 trees each were selected (705 trees in total) in a section of the orchard where less river rocks were present for practical purposes. This section of the orchard was divided into 15 plots of 3 x 7 trees each (5 repetition plots for 3 treatments) with buffer rows between each plot. The trial layout is illustrated in Figure 3.6 and can be described as a partially randomized block design

Figure 3.3: Experimental orchard selected as part of a bigger 'Nadorcott' mandarin orchard for the low flow drip experimental trial.

Figure 3.4: 'Nadorcott' mandarin trees established on ridges under white net planted 2.5 x 5 m apart (800 trees per ha)

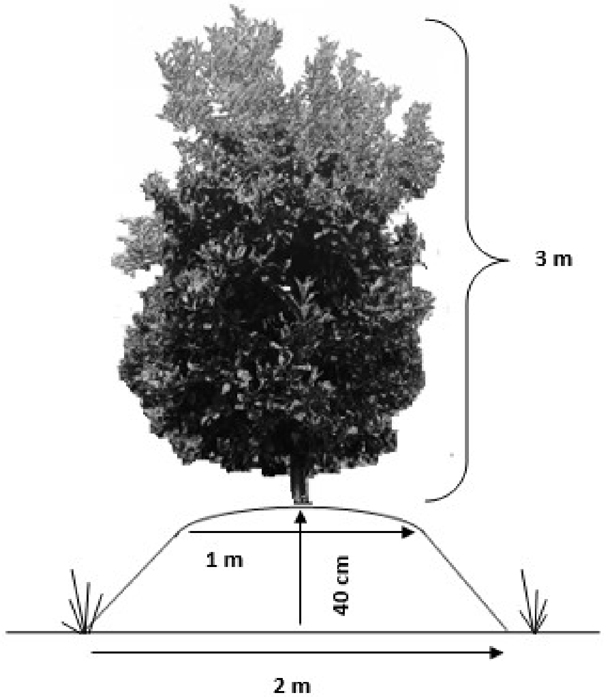

Figure 3.5: Average dimension of ridges and tree height in the experimental orchard.

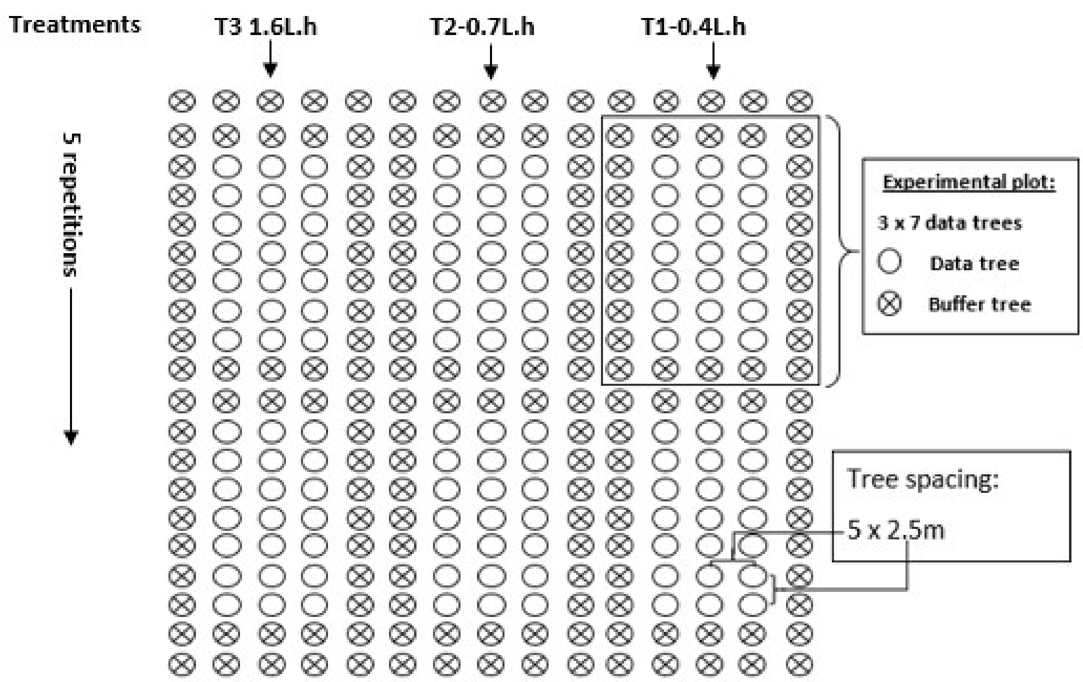

Figure 3.6: Illustration of the trial site layout with 5 repetitions of an experimental plot per drip discharge treatment.

3.2.2 Soil characteristics

Textural composition: To determine the textural composition of the soil, five soil samples were taken during the installation of the soil moisture sensors at nine plots, representing depths 0-15, 15-30, 30–45, 45-60 and 60- 80 cm. A total of 20 samples from four plots distributed over the trial site were analysed to determine the soil textural composition distribution with depth in the trial site. The pipette method described by Gee and Bauder (1986) was followed to categorize the soil into different particle size fractions. The following masses and formulas were used to determine the percentage sand, silt and clay fractions.

Sand fractions

Percentage sand fractions = (D * 100)/E

Silt and clay fractions

Percentage fine silt and clay (F) = [(A - C) * 1000 * 100]/[E x 25]

Percentage clay (G) = [(B - C) * 1000 * 100]/[E x 25]

Percentage fine silt = F - G

Percentage coarse silt = 100 – sum of sand fractions- F

where,

A = mass (g) of pipetted fine silt and clay

B = mass(g) of pipetted clay

C = mass (g) correction for calgon (0,011 g)

D = mass (g) of sandfraction on sieve

E = mass (g) of total ovendried pretreated soil sample

The textural composition of the soil is very uniformly distributed spatially over the trial site and with depth. The average soil textural composition is as follows: 88.48% sand, 8.88% silt and 2.64% clay (Table 3.1). The sand consists of majority medium (33.44%) and fine sand (36.96%) that may contributed to the soil's water holding capacity. According to the soil texture triangle (Figure 3.7) this soil is classified as a sandy soil.

The average bulk density (ρb) for this soil was 1.35 g. cm^{-3}, calculated from undisturbed soil samples taken at five depths representing 0-20, 20-40, 40-60, 60- 80 and 80-100 cm below soil surface (Table 3.2). Samples had a volume of 250 cm^{-3} and were oven dried at 105°C for 48 hours.

Table 3.1: Percentage particle size distribution with depth.

Percentage particle size distribution with depth (%)								
	Particle size (mm)							
Sampling depth (cm)	**Total sand**	**Coarse 2 -0.5**	**Medium 0.5-0.25**	**Fine 0.25-0.106**	**Very fine 0.106-0.053**	**Coarse silt**	**Fine silt**	**Clay**
0-15	88.95	7.57	34.89	36.53	7.13	4.66	3.92	2.47
15-30	88.07	8.40	33.83	36.24	8.53	4.49	4.75	2.70
30-45	89.01	6.61	34.49	36.81	8.11	4.45	4.00	2.55
45-60	87.30	7.49	31.34	37.97	9.18	5.98	3.92	2.80
60-80	89.06	9.42	32.66	37.24	8.45	4.39	3.82	2.72
Average	88.48	7.90	33.44	36.96	8.28	4.79	4.08	2.65

Figure 3.7: Soil texture triangle to determine soil texture class according to percentage sand, silt, and clay

Table 3.2: Soil bulk density with depth.

Sampling depth (cm)	Bulk density (g. cm^{-3})
0-20	1.36
20-40	1.36
40-60	1.33
60-80	1.34
80-100	1.33
Average	1.35

3.2.3 Soil moisture characteristics

To describe the soil water content fluctuation at various depths over time under continuous irrigation for the three different discharge rates, soil moisture characteristics applicable to such an irrigation regime were calculated as follow:

Field capacity (FC): Volumetric soil water content at -8 kPa determined from soil samples via the pressure pot method. The point at which the slope of drainage to extraction changes characterized by a rapid to slower decrease in SWC can be taken as the point of field capacity for a sandy soil (Zotarelli, Dukes and Morgan, 2010) (Figure 3.8). Due to difficulty of retrieving undisturbed soil samples from this sandy soil, soil characteristics were determined from loose soil samples that was packed to the desired soil bulk density calculated from undisturbed samples from bigger metal columns.

Lower level of easily available water (EAW_{lower}) : Volumetric soil water content at -100 kPa determined from soil samples via the pressure pot method (Myburgh, 1996; Pijl, 2001).

Permanent wilting point (PWP): 0.00385 [S + C%] + 0.013 (According to equation 2.4 in drip irrigation thesis of Isabella Pijl (Pijl, 2001)

Hillel (1998) mentioned that static points of water in the soil do not really exist and that water is always moving, but to describe the water content at which water is to be found in the soil during continuous irrigation and periods of active water uptake, it is convenient to establish ranges that soil moisture is maintained in.

The soil in this study was saturated at 0.37 $m^3.m^{-3}$. The FC (or EAW $_{upper}$) was calculated as 0.20 $m^3.m^{-3}$, denoting the capacity of the soil to held water against gravity after excess water has drained following water application via irrigation or rain (Datta and Stivers, 2017; Zotarelli, Dukes and Morgan, 2010). The lower level of easily available water was calculated as 0.07 $m^3.m^{-3}$ (at a matric suction of 100 kPa). The soil water content range between EAW $_{upper}$ and EAW $_{lower}$ is known to be easily available for uptake by plant roots and when water content drop below EAW $_{lower}$ water uptake becomes more difficult and water stress may occur (Pijl, 2001). The smaller this range, the more frequent irrigation would be required under conventional irrigation methods as the 'reservoir' of water available to the trees will be depleted quickly (Morgan *et al.*, 2005). The root depth (effective root zone) and allowable maximum depletion (%) would also then reduce the size of the reservoir. If calculations imply that frequent irrigation events need to take place in one day (pulse irrigation) a continuous irrigation approach via low flow drip would be a practical alternative. The high percentage of fine sand (< 0.25-0.106 mm) in this soil contributes to a higher water holding capacity than expected (Table 3.1). The PWP was calculated as 0.057 $m^3.m^{-3}$ for this soil, a soil water content at which severe water stress will occur (Datta and Stivers, 2017; Pijl, 2001; Zotarelli, Dukes and Morgan, 2010. The soil moisture retention curve is illustrated in Figure 3.8.

If the desired irrigation management depth (effective root zone) was at 40 cm and EAW content is 0.13 $m^3.m^{-3}$ (0.2-0.07) and allowable extraction is 20%, the EAW content would be equal to: 0.13 $m^3.m^{-3}$ x 400mm x 20 % = 10.4 mm when an event irrigation is due

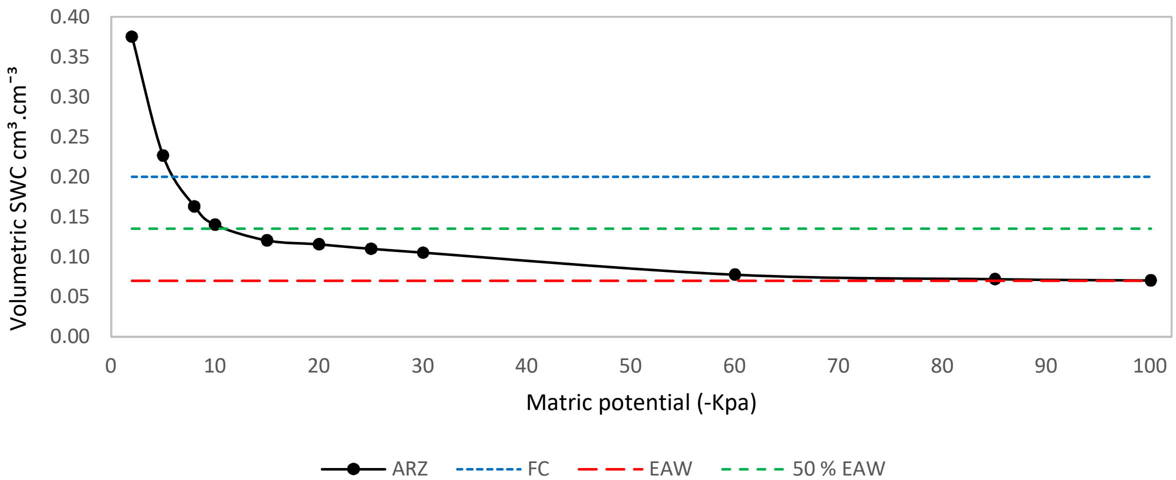

Figure 3.8 Soil water retention curve for the active root zone (ARZ) (0- 45cm) of the sandy soil on Denau farm, Hex River Valley (experimental site). FC represents the SWC at field capacity; 50% EAW represent SWC at 50 % of easily available water and EAW represents SWC at -100 kPa.

3.2.4 Saturated hydraulic conductivity (K_s)

K_s was determined with the KSAT instrument from METER Group (Environment). Undisturbed soil samples of 250 cm^3 sampled in 20 cm increments representing 0-20, 20-40, 40-60, 60-80 and 80-100 cm were used in this procedure. High K_s values (Table 3.3) were recorded for the upper 60 cm ranging between 1419 and 1165 $cm.day^{-1}$. The upper 60 cm can be described as the major root zone and area within the ridge. Lower K_s values were recorded in the 60-100 zone with the lowest K_s in the 80 -100 cm depth of 326 $cm.day^{-1}$. According to Hillel (1998) a sandy soil can have a K_s of 10^{-4} to 10^{-5} $m.sec^{-1}$ and a clayey soil 10^{-6} to 10^{-9} $m.sec^{-1}$.

Table 3.3 Saturated hydraulic conductivity ($cm.day^{-1}$) with depth.

	Ks ($cm.day^{-1}$)
Sampling depth (cm)	**Ks of soil samples**
0-20	1240
20-40	1419
40-60	1165
60-80	954
80-100	326

3.2.5 Irrigation system

This site was mainly selected due to the low flow drip irrigation system (0.7 $L.h^{-1}$, one meter spacing, double line) by which the orchards was irrigated since planting. This low flow drip system allows a large surface area to be irrigated in one shift with a system flow rate of 2.5 to 3.5 m^3/ha/hour according to the climatic crop water demand (C. Malan, personal communication). To study the effect of continuous irrigation with different discharge rate emitters on soil water distribution, root distribution and crop response, higher (1.6 $L.h^{-1}$, 0.5 meter spacing) and lower (0.4 $L.h^{-1}$ -ultra low flow drip, one meter spacing) discharge rate drippers were added to the irrigation system. The 1.6 $L.h^{-1}$ drip system received water with the original system when the pump was on. An additional tank was installed with a smaller pump from which the 0.4 $L.h^{-1}$ drip system received water due to a longer irrigation cycle that occasionally continues when the main pump was switched off. The irrigation cycles were automatically controlled by a Netafim NMC Junior controller . Each drip system had a flow meter to record the volume of water (m^3) that each treatment received with every irrigation event . Each tree row in the trial had double drip line spaced 80 cm apart placed on the soil surface of the ridge. Thus the 0.7 $L.h^{-1}$ and 0.4 $L.h^{-1}$ (1 m spacing, double drip line) drip system had 5 drippers per tree and the 1.6 $L.h^{-1}$ drip system (50 cm spacing, double drip line) resulted in 10 drippers per tree.

The treatments commenced on the 1st of November 2019 after flowering and fruit set took place and continued until 28 December 2020. Thus, flowering and fruit set occurred under control conditions (0.7 $L.h^{-1}$ discharge rate).

Figure 3.9: (1) Layout of the pumphouse with extra 2200L JoJo tank for supplementing the 0.4 L.h drip system (2) Three flow meters for each mainline supplying water to the irrigation plots. (3) Netafim NMC Junior controller.

3.3 Treatments

The treatments (T) consisted of three different emitter discharge rates, resulting in three different durations of irrigation cycles, a short, medium, and long irrigation cycle (all continuous) applied in 15 experimental plots in total as explained in the trial layout. Each treatment received the same volume of water at each irrigation event. The treatments were as follow:

Table 3.4: Description of the three drip irrigation treatments within this trial.

Treatment	Description
T1	0.4 $L.h^{-1}$ discharge rate (ultra-low flow drip), continuous irrigation (daily water requirement)
T2	0.7 $L.h^{-1}$ discharge rate (ultra-low flow drip), continuous irrigation (daily water requirement)(Control)
T3	1.6 $L.h^{-1}$ discharge rate (ultra-low flow drip), continuous irrigation (daily water requirement)

The volume of water applied at each irrigation event was according to recommendations from an irrigation programme (Agriwiz), mainly based on the climatic demand (Reference evapotranspiration; ET_o (Penman-Monteith FAO 56 PM) that takes canopy cover, tree age and orchard conditions also into consideration. Water was applied daily during the high water demand season (November to May) and every second or third day during the higher rainfall periods (June to August). This approach aims at maintaining soil water near field capacity (-8 to -10 kPa) and allows minimal extraction.

As the orchard was established under T2- 0.7 $L.h^{-1}$ discharge rate and served as the control, the irrigation duration of the other treatments was adapted according to the discharge rate to ensure the same volume of water is applied at every irrigation. Thus, the irrigator scheduled according to the 0.7 $L.h^{-1}$ discharge rate, (the same as the rest of the orchard) and the other treatments were adapted by multiplying the control irrigation duration with a factor as follow:

T1-0.4L.h^{-1} : Irrigation duration of T2 x 1.75

T3-1.6L.h^{-1} : Irrigation duration of T2 x 0.22

The factor to adapt the irrigation duration to ensure the same volume of water was applied was determined as follow (Table 3.5)

Factor = Control flow (Total $L.h^{-1}$)**/** Treatment flow (Total $L.h^{-1}$)

Total flow ($l.h^{-1}$) per treatment = (total length of dripper pipe **x** discharge rate)**/** spacing

Total length of dripper pipe per treatment = 47 trees **x** 2.5 m (distance between trees) **x** 5 (rows per treatment) **x** 2 (double drip line per tree row) = **1175 m**

Table 3.5: Multiplication factors to adapt irrigation cycles of T1-0.4L.h and T3-1.6L.h to ensure the same volume of water is applied with each irrigation event.

Treatment	Total flow per treatment (L/h)	Litres per hour	Factor
T1- 0.4 $L.h^{-1}$	(1175 x 0.4)/1	470	(822.5/470) = **1.75**
T2- 0.7$L.h^{-1}$	(1175 x 0.7)/1	822.5	(822.5/822.5) = **1**
T3- 1.6$L.h^{-1}$	(1175 x 1.6)/0.5	3760	(822.5/3760) = **0.22**

The general irrigation cycles were as follow: T2- 0.7$L.h^{-1}$(control) started at 09:00 and continued until 15:00 (6 hours), T3- 1.6$L.h^{-1}$ started at 09:00 and continued until 10:20 (1 hour 20 min) and T1- 0.4$L.h^{-1}$ started at 04:30 in the morning and continued until 15:00 (10 hours 30min). A longer irrigation cycle (control treatment) was applied every two weeks when needed (determined by probe readings) and the other treatments were adapted proportionally. These irrigation schedules were programmed into the Netafim NMC Junior controller. Each irrigation event consisted of a nutrient solution and the concentration was kept constant for all three treatments. Only the long irrigation cycles consisted of clean water

3.4 Root studies

3.4.1 Profile wall method

On the 10th of October 2019 after the spring flush, the root distribution of the experimental orchard was studied via the profile wall method. Six profile pits were dug in total, distributed over the experimental orchard to determine the root distribution before treatments were applied. These root studies represent the control treatment (0.7 $L.h^{-1}$ discharge rate) under which the orchard was established. The profile pits were dug between adjacent trees, parallel with the ridge and drip line, 2m in length between trees, one meter deep and one meter wide to study roots in the ridge (Figure 3.10). Soil was removed from the roots and roots were cut off with pruning shears ~ 1 cm from the wall. A grid with 10cmx10cm blocks was placed against the trench wall between trees. All the roots inside the individual blocks were counted and plotted onto grid paper. Roots were divided into size categories:

fine (< 2 mm), medium (2-5 mm), thick (5-10 mm) and very thick (>10 mm) and noted accordingly each with its own symbol.

In October 2020 follow up root studies were conducted. Three new profile pits were dug in each treatment (total of nine) to study the effect that change in emitter discharge rate and the resulting water distribution patterns had on root distribution in the soil profile. The position of the profile pit in relation to the trees and drippers were kept constant. The same procedure as explained for the pre - treatment root studies in October 2019 was followed .

Fine roots are expected to adapt rapidly to irrigation regimes as elongation rate of Carrizo citrange roots can increase from 1.6 to 6.5 mm.day^{-1} during early Spring (Bevington and Castle, 1985).

Figure 3.10. Root distribution study via the profile wall method. Profile pits of two meter in length between adjacent trees (parallel with the ridge), one meter deep and one meter wide were dug.

3.4.2 Chemical analysis

During root studies in October 2020, three soil samples were collected from every profile pit in the drip zone underneath a dripper, representing the 0-20 cm, 20-40 cm, and 40-60 cm depth zone. These samples were analysed by Labserve Analytical Services.

3.5 Soil water content measurements

3.5.1 Root zone water content fluctuation

After root distribution observations were made, Decagon sensors connected to an EM50 data logger (Decagon Devices, Pullman, Washington, USA) were installed at incremental soil depths. Five Decagon soil moisture sensors of various types (Figure 3.11) were installed at 15, 30, 45, 60 and 80 cm below the soil surface. These depths represent the zones above, in and below the active root zone. The cables of the sensors that connected to the EM50 data logger were threaded through an 80 cm long and 25 mm thick conduit pipe (Figure 3.12). Holes were made on the side of the conduit pipe at the depth where sensors were installed. The sensors were installed underneath, 5 cm away from a dripper, 30-40 cm from the tree trunk on the southern side of the tree. This was repeated within nine experimental plots, resulting in three repetitions for three different treatments of drip irrigation. A total of 45 Decagon sensors were installed to capture data of soil water content changes within this trial.

Soil water content was recorded every 30 min during the experimental period from 26 October 2019 to August 2020. The data was collected in field by downloading the stored data onto a laptop. Observing water content changes at these five depths can clearly portray the behaviour of water under the three different drip irrigation treatments in relation to soil properties and root water uptake. Line graphs were constructed to visualize volumetric soil water content fluctuation and to interpret the soil water content behaviour over time at the chosen depths within the soil profile. Calibration curves (Appendix) were determined for all sensors according to the methodology provided by METER Group (Cobos and Chambers, 2002).

The Decagon sensors installed at 15 and 30 cm (5 TM and 5 TE) were able to record temperature in °C from November 2019 to August 2020.

3.5.2 2-Dimensional water content distribution

Depicting the 2-dimensional water distribution over time under drip irrigation have received a lot of attention with the advance in irrigation and water measurement technology. Majority of the information available on water distribution under drip irrigation derives from simulations (Soulis, Elmaloglou and Dercas, 2015; Phogat *et al.*, 2012; C. M Cote *et al.*, 2003). In - field measurements (orchard conditions) are time consuming and expensive.

To visualize the 2-Dimensional water distribution resulting from the three different dripper discharge rates, 11 PVC access tubes were installed at a single tree, five tubes between two drippers parallel to the drip line on the ridge and six perpendicular to the drip line between two adjacent drippers (Figure 3.13). Holes were drilled 20 cm apart with a Thomson auger to insert the access tubes to take readings with a Sentek Diviner 2000 capacitance probe. Three readings were taken per tube and averaged to represent SWC at that position at that given time. This was repeated for every treatment, one tree in block 2, block 3 and block 5 for treatment 1, 2 and 3 respectively. Trees of similar height and volume were chosen for this experiment. Soil water content readings were taken on the 19th of October and the 28th of December when a short and longer irrigation event took place respectively to visualize horizontal and vertical distribution and fluctuation of the wetted soil volume created under a dripper resulting from three different irrigation treatments, ultra-low flow drip, low flow drip and daily conventional drip irrigation. On the 19th of October when a short irrigation cycle was applied readings were taken at 07:00, 09:00, 10:00, 12:00, 14:00 and 16:00. On the 28th of December 2020 when a long irrigation cycle was applied readings were taken at 08:30, 11:00, 14:00, 15:30 and 19:00. Contour graphs were generated from the data collected on these respective days.

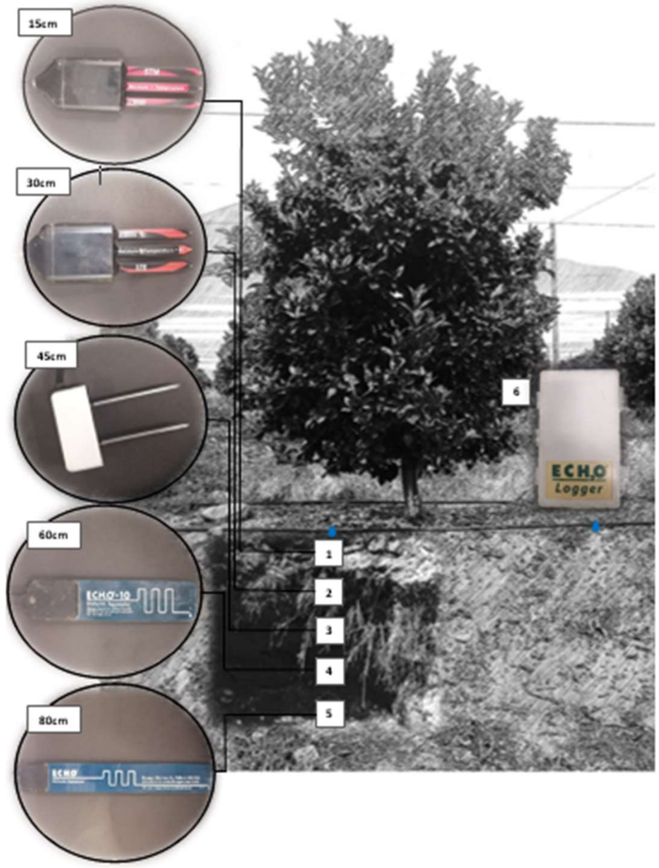

Figure 3.11: Decagon soil moisture sensors installed at various depths in and below the root zone connected to an Em50 data logger (6). At 15 cm: 5TM soil moisture/temperature sensors (1) at 30 cm: 5TE soil moisture/temperature sensor (2) at 45 cm: GS1 soil moisture sensor (3) at 60 cm: EC10 soil moisture sensor (4) at 80 cm: EC20 soil moisture sensor (5).

Figure 3.12: Decagon soil moisture sensors threaded through conduit pipe and installed at depths in and below the root zone connected to an EM50 data logger to store data.

Figure 3.13: PVC access tubes installed 20 cm apart at a tree around a dripper across the ridge and parallel with the ridge to measure soil water content distribution with the Sentek Diviner 2000 capacitance probe to visualize spatial distribution of the wetted soil volume.

3.6 Crop response

3.6.1 Rate of fruit growth

From 31st of Jan 2020 the rate of fruit growth was recorded at ± 2-week intervals. One tree of similar size in every plot of the experimental trial was selected, thus 15 trees in total. Ten fruit distributed around the tree, about 1.5 m from the soil surface on each tree was selected and labelled. Citrus fruit have a spherical shape and a good correlation exist between fruit diameter and volume (Mostert, 1999). The diameter of every fruit was measured with an electronic calliper in mm to the second decimal from Jan 2020 until July 2020, three weeks before harvest took place. Thus, a total of 150 fruit were measured (50 in each treatment). No fruit diameter measurements could be taken during April 2020 due to the COVID-19 lockdown regulations.

3.6.3 Yield and fruit size distribution

On 12 August 2020 a few days prior to the commercial harvest of the orchard, the trial site was harvested. Three trees of similar size in every experimental plot were randomly selected in each treatment. Thus, a total of 45 trees (15 for each treatment) were selected to contribute to yield and size distribution data.

Fruit size distribution: Before the trees were stripped, the diameter of 50 fruit from each randomly selected tree were measured with an electronic calliper (Figure 3.14). Thus, a total of 15 x 50 fruit contributed to fruit size distribution data for each treatment. Fruit positioned in the window between 1 m and 1.6 m height around the tree were measured.

Yield: To record the yield data between treatments all the selected trees were stripped of all its fruit and the fruit mass of every tree were recorded separately in the orchard with a field scale, in kilograms (kg) to the second decimal.

Since only 15 trees were selected to represent yield data for each treatment, the data is reported in mass per tree. This expression is not used in a commercial setup. By multiplying the average $kg.tree^{-1}$ with the trees per ha (800) an estimation of expected $tons.ha^{-1}$ can be calculated.

3.6.4 Fruit quality

Prior to the harvest, two samples (one sample = 12 fruit) were collected from each experimental plot. Fruit from randomly selected trees of similar size (average size of ~ 60 - 64 mm) were sampled from the sun and shade side within a plot and pooled to make up a sample. A total of 10 samples (120 fruit) contributed to internal quality data for each treatment, a total of 360 fruit. The fruit samples were collected by Citrii Agri Services and analysed by a nearby packhouse. The samples were analysed for °Brix, acidity, and juice percentage.

Figure 3.14: (a) Electronic calliper used to collect fruit size distribution data. (b) Well coloured 'Nadorcott' mandarin fruit.

3.7 Statistical Analyses

All raw data collected were captured by Microsoft Excel® to sort and calculate means. The captured data were subjected to an analysis of variance (ANOVA) and least significance difference (LSD) values were calculated by means of Statistica 14 and R package lmertest version 3.1-0 to aid comparison between treatment means. Analyses with *p* values ≤ 0.05 were to be considered significantly different.

Chapter 4: Effect of drip discharge rate on soil water dynamics under irrigated 'Nadorcott' mandarin (*Citrus reticulata* Blanco)

4.1 Introduction

Drip irrigation became a tool for horticulturists to regulate plant growth through precise and sensitive irrigation management, especially in citrus production (Falivene, 2005; Glenn, 2000; Schoeman, 2002). The total planted area of late maturing mandarins increased with 21% from 2014 to 2015, more than any other cultivar group (Cronje, 2016) accompanied by drip irrigation and fertigation practices and became a popular research field. According to a water wheel article (July 2018 edition) the Western Cape contributes the most to total area irrigated followed by Limpopo and the average water use to be 5874 $m^3.ha^{-1}$ and 8841 $m^3.ha^{-1}$ for each province respectively.

Irrigating according to estimated evapotranspiration (ET_c), which is the reference evapotranspiration (ET_o) multiplied with a crop factor (Kc), accompanied with soil moisture readings advanced citrus irrigation scheduling. Under a conventional irrigation regime irrigating on alternate days, the soil act as a reservoir and water availability to the plant depends on the soil's water holding capacity (Novák and Havrila, 2006; Lord and Jensen, 1975). On sandy soils with low water holding capacity irrigation via conventional drippers on sandy and rocky soils involves a few short irrigation pulses daily that may lead to under and over irrigation in an orchard due to filling and emptying of the irrigation system. The development of low delivery rate drippers addressed this problem by improving the hydraulic application uniformity and has continuous irrigation as a further outcome (C. Malan, personal communication). Continuous drip irrigation involves decreasing the application rate of the irrigation system to balance with the maximum daily water use over the consumptive period (C. Malan, personal communication), steering away from scheduling as we know it and relying less on the soil's capacity to retain water. The aim of these new drip fertigation intervention is to optimise production and fruit quality while reducing leaching by means of applying water at a low application rate and a high frequency to meet crop demand (Falivene, 2005; Phogat et al., 2014).

By closely observing graphs obtained from soil moisture sensors, the efficiency of an irrigation system and scheduling can be evaluated by measuring soil water content (SWC) and the fluctuation thereof in and below the root zone (Zotarelli, Dukes and Morgan, 2019; Fares and Alva, 2000).

Sokalska *et al*. (2009) stated that a key to increase the efficiency of drip irrigation, the shape of the wetted soil volume should be adjusted to the main root mass distribution of the irrigated plants. However, it is known that with change in drip delivery rate the patterns of soil water distribution may differ (Bar-Yosef, 1999; Assouline, 2002). The 3-Dimensional water distribution under a dripper is a result of various interrelated factors including the soil hydraulic properties (soil texture), drip discharge rate, frequency of irrigation, volume of water applied per irrigation, total amount of water in the soil as well as root distribution patterns and water uptake rates (Schwartzman and Zur, 1987; Assouline, 2002; Hopmans, Hanson and Gardenas, 2005)

Various authors (Bar-Yosef, 1999) (Skaggs, Trout and Rothfuss, 2010; Fan *et al.*, 2018) have concluded that increasing the drip delivery rate results in increased horizontal water distribution and a decrease in the vertical component of the wetted soil depth.

Cote *et al.* (2003) concluded a larger wetted soil volume with decreasing discharge rate with an increased radius and wetted depth. Fan *et al.* (2018) found a positive correlation between initial SWC and horizontal and vertical water distribution thus a larger irrigated soil volume. Field observations under low flow drip systems seem to indicate no saturated zone under the dripper and a greater wetted soil volume compared to conventional drippers (Assouline, 2002). Decreasing the application rate but applying the same volume of water increases the dimensions of the wetting pattern due to decreased average water content behind the wetting front (Cote *et al.*, 2003). A simulation study by Skaggs, Trout and Rothfuss (2010) showed that low application rate (by means of low delivery rate drippers or pulse irrigation) and low antecedent soil water content slightly increases the horizontal water distribution relative to the wetted depth. They ascribed it to longer irrigation times and not to a flow phenomenon. Increasing the antecedent soil water content also increased the dimension of the wetted soil volume but, in both directions due to less pore space to hold applied water

Pulse irrigation is also seems to increase horizontal water distribution (Elabadin, Ibrahim and Omara, 2014). Others also found that similar water distribution patterns may results from pulse irrigation and continuous irrigation with low application rates (Assouline, 2002).

Contradicting results between authors may be ascribed to application rates of greater magnitude used in prior studies causing water to pond, jeopardizing the distribution of water (Skaggs, Trout and Rothfuss, 2010).

Due to 3-dimentional water distribution from a dripper, gradients of water content form, with decreasing water content towards the periphery of the wetted soil volume (Bravdo and Proebsting, 1993). A few authors have confirmed that with decreasing the discharge rate results in less sharper gradients of soil water content within the wetted soil volume from the emitter towards the periphery (Cote *et al.*, 2003; Assouline, 2002).

Phogat *et al.,* (2014) concluded steady water content levels throughout the season at 10 cm (0.2 $cm^3.cm^{-3}$) and 80 cm (0.1 $cm^3.cm^{-3}$) depth, but more fluctuation at 25 and 50 cm depth, measured weekly in a drip irrigated (1.6 $L.h^{-1}$) mandarin study, irrigating according to estimated crop evapotranspiration (ETc).

Segal, Ben-gal and Shani (2006) found steadier water content maintained at high relative water content levels associated with eight pulses and continuous irrigation with average volumetric soil water content of 0.23 $cm^3.cm^{-3}$ and 0.21 $cm^3.cm^{-3}$ respectively. Assouline (2002) also concluded that low delivery rate drip reduced water content fluctuation in the active root zone.

High frequency water application maintains a high SWC in a portion of the root zone and minimizes drying and wetting fluctuation (Bresler and Yasutomi, 1990; Segal, Ben-gal and Shani, 2006) which would imply increased water flow and nutrient availability to roots (Hillel, 1998; Segal, Ben-gal and Shani, 2006).

Water distribution patterns under conventional drippers have been well documented but not for low discharge rates or a continuous irrigation approach (Assouline, 2002; Assouline *et al.*, 2006). Meagre results are available on seasonal soil water fluctuating and water distribution patterns in relation to water uptake patterns of horticultural crops under low discharge rate continuous drip irrigation. The objectives of this study are therefore to evaluate seasonal water content fluctuation with depth associated with a continuous drip irrigation approach of 4-year-old 'Nadorcott' mandarin trees via 1.6 $L.h^{-1}$, 0.7 $L.h^{-1}$ and 0.4 $L.h^{-1}$ discharge rate drippers and to characterise the 2-Dimensional water content distribution of the wetted soil volume.

4.2 Results and discussion

During the period of the trial, highest rainfall was recorded in June and July, 77 mm, and 81 mm respectively with a total of 340 mm (October 2019 to October 2020). Reference evapotranspiration (ET_o) followed a typical bell shape curve with highest ET_o in December reaching 190mm and lowest during June, 51.57 mm (Figure 4.1). Monthly irrigation applied followed the same trend as ET_o values with greatest volume of water applied from November 2019 to February 2020, decreasing towards July in the fruit ripening and harvesting period. From November 2019 until November 2020 an average of 4700 $m^3.ha^{-1}$ was applied per treatment. An overview of irrigation volumes per month can be seen in Table 4.1

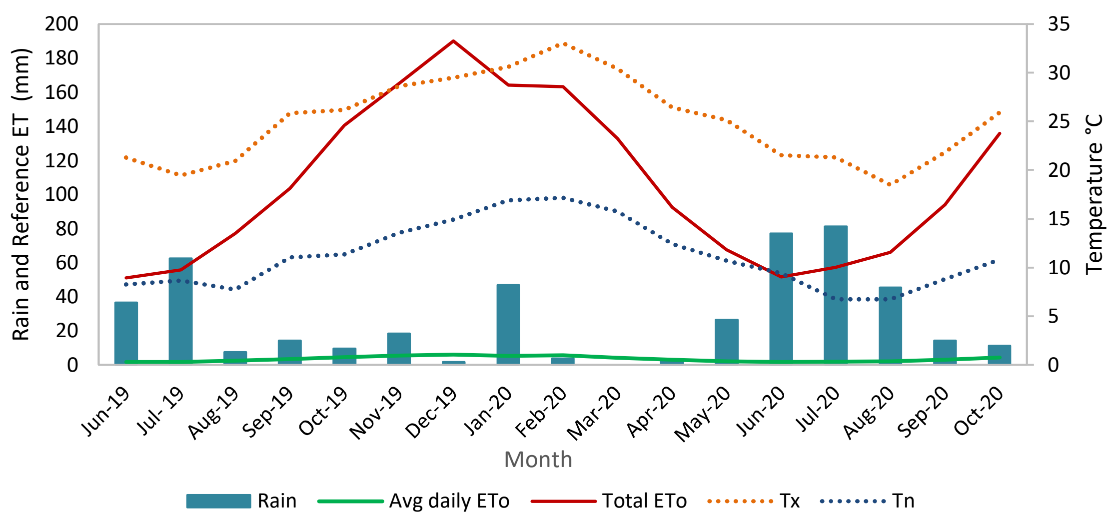

Figure 4.1: Climatic conditions during the period of the trial. Monthly rainfall, reference evapotranspiration (ET_o) and average daily ET_o are expressed in mm and monthly maximum and minimum temperatures in °C.

Table 4.1 Monthly irrigation amounts expressed in m³.ha⁻¹, mm, and corresponding total and average ETo values. Applied crop factor is equal to total irrigation in mm divided by the total ETo per month.

Month of the year	Total $m^3.ha^{-1}$			Total $mm.ha^{-1}$					Applied crop factor		
	T3-1.6 $L.h^{-1}$	T2-0.7 $L.h^{-1}$	T1-0.4 $L.h^{-1}$	T3-1.6 $L.h^{-1}$	T2-0.7 $L.h^{-1}$	T1-0.4 $L.h^{-1}$	ET_o mm	Avg ET_o mm/day	T3-1.6 $L.h^{-1}$	T2-0.7 $L.h^{-1}$	T1-0.4 $L.h^{-1}$
Nov 2019	432.0	434.9	389.1	43.2	43.5	38.9	165.2	5.5	0.26	0.26	0.24
Dec 2019	538.7	587.0	575.1	53.9	58.7	57.5	190.0	6.1	0.28	0.31	0.30
Jan 2020	560.5	679.1	649.0	56.1	67.9	64.9	164.1	5.3	0.34	0.41	0.40
Feb 2020	359.3	379.3	460.4	35.9	37.9	46.0	163.1	5.6	0.22	0.23	0.28
Mar 2020	591.0	581.7	559.6	59.1	58.2	56.0	132.9	4.3	0.44	0.44	0.42
Apr 2020	481.2	506.7	490.8	48.1	50.7	49.1	92.6	3.1	0.52	0.55	0.53
May 2020	310.0	321.4	337.9	31.0	32.1	33.8	67.5	2.2	0.46	0.48	0.50
Jun 2020	229.8	268.3	292.4	23.0	26.8	29.2	51.6	1.7	0.45	0.52	0.57
Jul 2020	62.3	85.8	74.2	6.2	8.6	7.4	57.3	1.9	0.11	0.15	0.13
Aug 2020	186.8	178.9	212.4	18.7	17.9	21.2	66.1	2.1	0.28	0.27	0.32

4.2.1 Seasonal soil water content distribution in response to different drip irrigation treatments

Monitoring soil water content (SWC) at depths 15, 30, 45, 60 and 80 cm with various soil moisture sensors (Decagon Devices, see Appendix Figure A2) and Em50 data loggers in 30 min intervals from November 2019 to August 2020 allowed us to visualize SWC patterns in and below the active root zone. The mean weekly SWC observed at depths 15cm, 30cm, 45cm (averaged as the active root zone (ARZ)) and 60cm and 80 cm (averaged as the lower root zone (LRZ)) are illustrated in Figure 4.2. The data are expressed as means of all the replicates. Highest SWC in the ARZ was associated with T1-0.4 $L.h^{-1}$ with volumetric SWC values ranging between 0.23 and 0.14 $cm^3.cm^{-3}$, occasionally above field capacity (FC), followed by T2-0.7$L.h^{-1}$, 0.2 to 0.07 $cm^3.cm^{-3}$, and T3-1.6$L.h^{-1}$ 0.158 to 0.047 $cm^3.cm^{-3}$ respectively. These volumetric SWC values of all three treatments corresponded to soil water potential ranging from -2.5 kPa and -100 kPa (Figure 3.8; Chapter 3). Soil water between FC and 100 kPa is often considered as readily available or easily available water (Myburgh, 1996; Pijl, 2001). SWC in the LRZ remained fairly constant under T1-0.4$L.h^{-1}$ during the research period with values ranging between 0.096 and 0.026 $cm^3.cm^{-3}$. SWC in the LRZ with T2-0.7$L.h^{-1}$ and T3-1.6$L.h^{-1}$ followed a similar trend, initially lower than T1-

0.4L.h^{-1} and increasing towards the end of July with higher SWC compared to T1-0.4L.h^{-1}. From November to February dry conditions was observed under T3-1.6L.h^{-1} and only

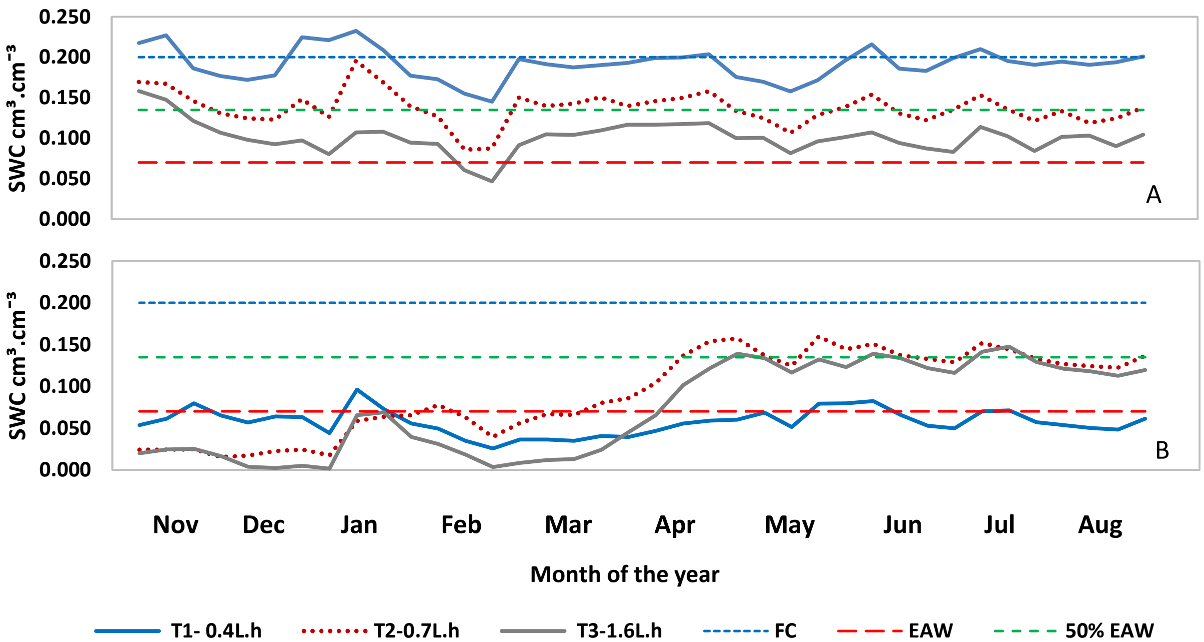

Figure 4.2: Soil water content variation in the active root zone (ARZ)(A) and lower root zone (LRZ)(B) under different treatments of drip irrigation from November 2020 until August 2021. Field capacity (FC) denotes for volumetric soil water content at -8 kPa and easily available water content (EAW) equals to volumetric soil water content at -100 kPa

increased after a rain event.

Similar and relatively high SWC was observed in the LRZ with T2-0.7L.h^{-1} and T3-1.6L.h^{-1} from April to August and SWC at 50% EAW in both the ARZ and LRZ with T2-0.7L.h^{-1}, suggesting a uniform distribution of water. During this period average higher SWC was observed in the LRZ than the ARZ suggesting that more water is moving beyond the ARZ and increased rainfall adding to this water movement. During the summer months (November to March) a steeper gradient in SWC between the ARZ and LRZ was observed in all three treatments, showing that even when more water was applied during this period (Table 4.1), the irrigated water resides in the ARZ for rapid water uptake under daily drip irrigation. This observation is the aim of irrigation and fertigation strategies like open hydroponic systems (OHS) and Advanced citrus production systems (ACPS) to maintain high SWC in the root zone via pulsing or a continuous irrigation approach (Falivene,2005; Schumann, Syvertsen and Morgan, 2009).

Water fluctuation in the ARZ and LRZ followed similar trends in all three treatments as the wetted soil volume expanded and shrunk in relation to the volume of water applied. Figures 4.3 a, b, and c clearly shows the trend of water fluctuation at the various depths in the soil profile during December 2019, April 2020, and July 2020. If they are interpreted by the concept of uptake **>** application **=** drying out; uptake **=** application = stay constant; uptake < application = addition, it seems as if all three treatments follow a general trend of uptake = application. This is clear by the constant SWC levels maintained at the various depths. During December however, a slight decreasing trend was observed in T3-1.6L.h^{-1} in the upper and lower part of the soil profile, suggesting uptake > application, portraying a soil profile that is drying out. This trend was also observed at 45 cm in T2-0.7L. h^{-1} that may be due to more roots contributing to extraction at this depth. During April, at the lower depths of the profile, uptake was smaller than application in T2-0.7L.h^{-1} and T3-1.6L.h^{-1} and build-up of SWC occurred at 80 cm depth.

Overall T1-0.4L.h^{-1} resulted in the most constant SWC at all depths during different months of the year as seen in Figure 4.3 a to c, suggesting application = uptake. This agrees with observations from Assouline (2002) and Segal *et al.* (2006) that low discharge rate continuous irrigation reduced water fluctuation in the active root zone. This also point to very accurate crop factors accompanied by an effective drip irrigation system applying the daily water demand. Segal *et al.* (2006) reported steady soil water content in the upper 30 cm at relatively high soil water status (0.22 $cm^3.cm^{-3}$) via 1 L.h^{-1} drippers.

4.2.2 SWC fluctuation at 45 cm depth

Irrigation depth was occasionally affected up to 45 cm by all three treatments (Figures 4.3 a to c). Overall, applying water at an ultra-low discharge (T1-0.4L.h^{-1}) resulted in significantly higher SWC at 45 cm depth from November until August compared to the low discharge treatment (T2-0.7L.h^{-1}) and the daily conventional treatment (T3-1.6L.h^{-1}) (Figure 4.4). Average SWC recorded at 45 cm were 0.156 $cm^3.cm^{-3}$, 0.09 $cm^3.cm^{-3}$ and 0.07 $cm^3.cm^{-3}$ for T1-0.4L.h^{-1}, T2-0.7L.h^{-1} and T3-1.6L.h^{-1} respectively.

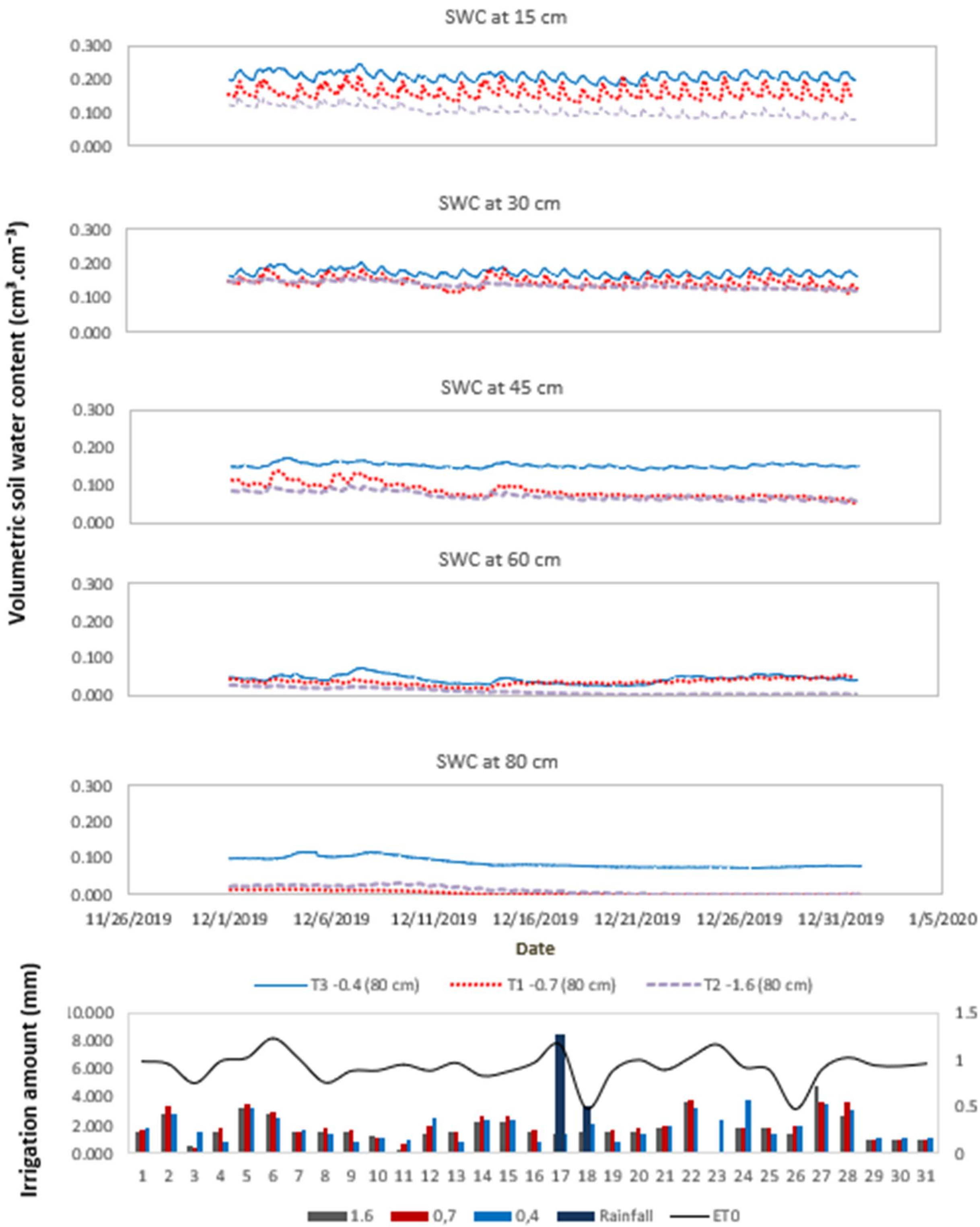

Figure 4.3 a: Average soil water content during December 2019 at different depths of the root zone in response to different treatments of drip discharge rates.

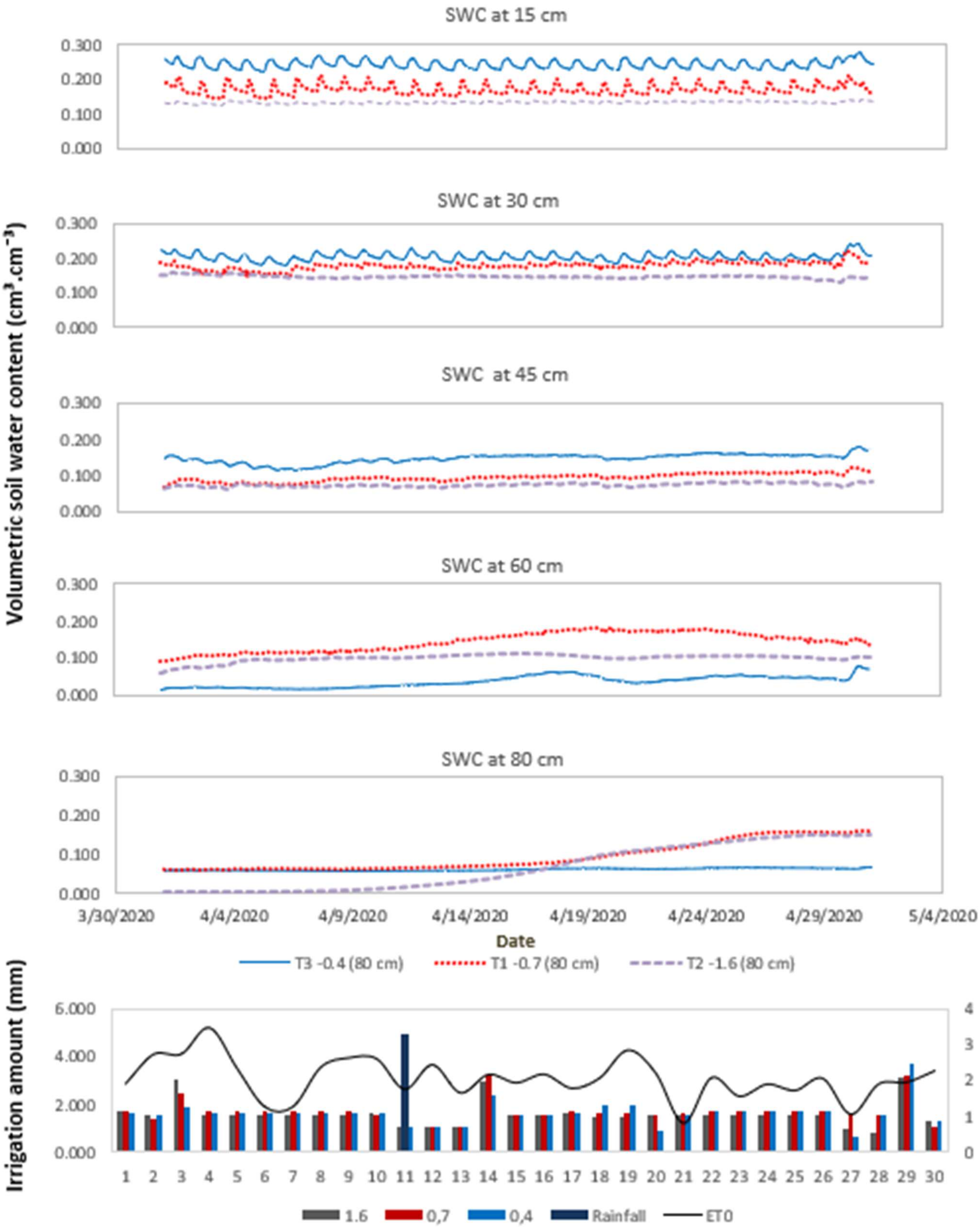

Figure 4.3 b: Average soil water content during April 2020 at different depths of the root zone in response to different treatments of drip discharge rates.

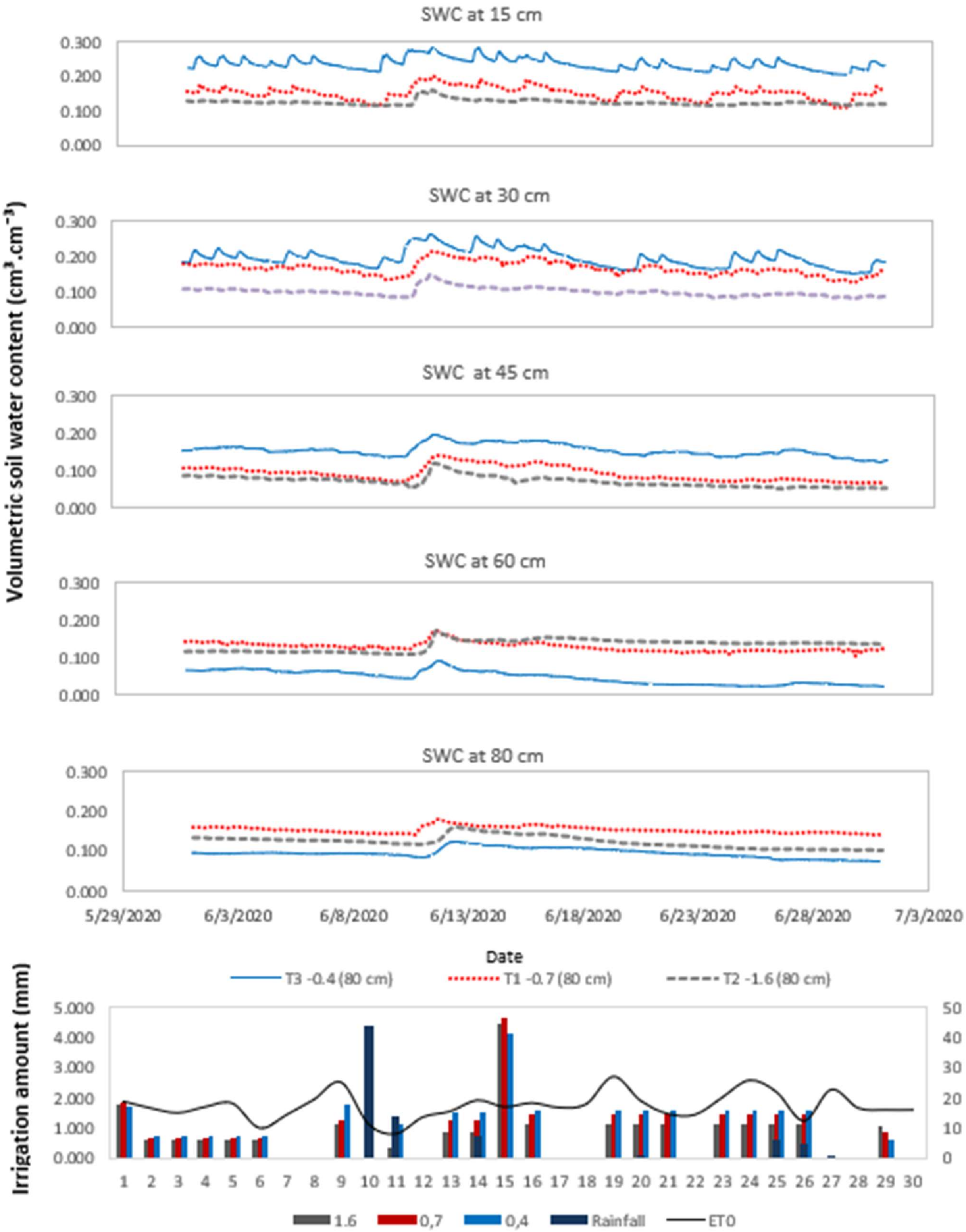

Figure 4.3 c: Average soil water content during June 2020 at different depths of the root zone in response to different treatments of drip discharge rates.

During December and January when an average of 600 $m^3.ha^{-1}$ was applied per month, SWC at 45 cm under T1-0.4L.h^{-1} was significantly higher than T2-0.7L.h^{-1} and T3-1.6L.h^{-1} ranging from 0.17, 0.12 and 0.095 $cm^3.cm^{-3}$ respectively (Figure 4.5). This refers to SWC levels above 50% EAW for T1-0.4L.h^{-1} and EAW for T2-0.7L.h^{-1} and T3-1.6L.h^{-1} . In April when 49 mm was applied in total, during the rapid fruit growth stage (**see Figure 6.1 Chapter 6**) SWC in T1-0.4L.h^{-1} and T2-0.7L.h^{-1} did not differ significantly although higher SWC was associated with T1-0.4L.h^{-1} (above 50 % EAW) compared with T2-0.7L.h^{-1} (between 50% EAW and EAW). T2-0.7L.h^{-1} and T3-1.6L.h^{-1} (on average at EAW, -100 kPa) did not differ significantly, but T1-0.4L.h^{-1} and T3-1.6L.h^{-1} did. The same trend as in the ARZ (Figure 4.2) was observed at 45 cm depth with average SWC decreasing with increase in discharge rate. During June to July the same trend was observed in SWC but decreasing to under EAW on average for T3-1.6L.h^{-1}. Thus, a decrease in drip discharge resulted in an increase of SWC at 45 cm. These seasonal differences in SWC at 45 cm depth may be due to differences in the shape of the wetted soil volume, known to change with discharge rate. (Bar-Yosef, 1999; Fan *et al.*, 2018). Bar-Yosef (1999) mentioned that lowering the discharge resulted in deeper irrigation depth. Another explanation could be the timing of irrigation and the SWC at the commencement of irrigation for each treatment. The ultra-low flow treatment (T1-0.4L.h^{-1}) started before the crop is using water and the soil was at a higher soil moisture status resulting in higher water conductivity (Fan *et al.*, 2018) and wetter conditions deeper in the soil profile compared to T2-0.7L.h^{-1} and T3-1.6L.h^{-1}.

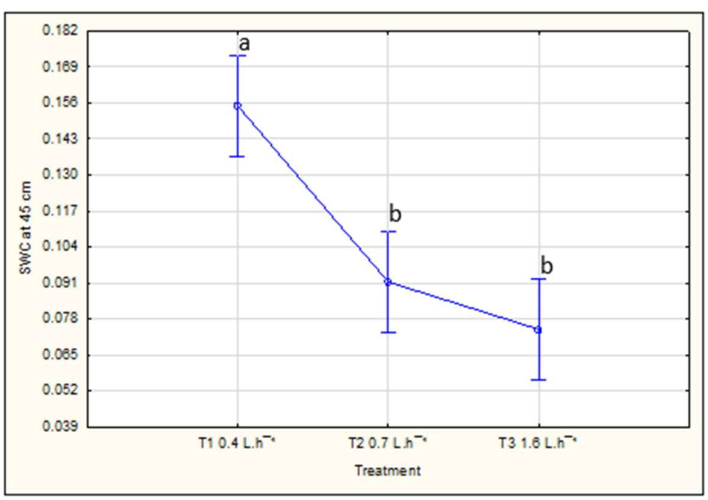

Figure 4.4: Average volumetric soil water content at 45 cm depth from Nov 2019 to Aug 2021 under a dripper. Data are means from November 2019 to August 2020). Treatment means with different letters between columns differ significantly ($p \leq 0.005$). Vertical bars denote ± SE

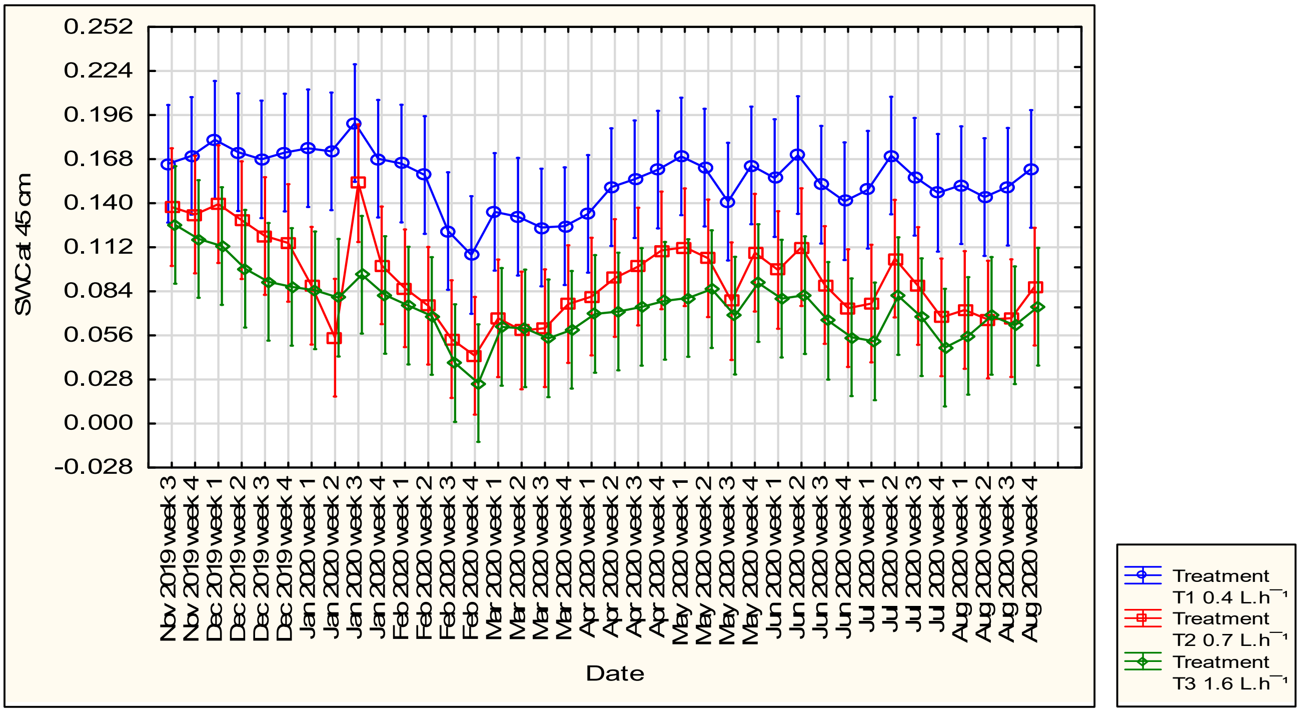

Figure 4.5: Weekly volumetric soil water content fluctuation at 45 cm depth under a dripper. Vertical bars denote ± SE

4.2.3 SWC distribution with depth during high water demanding periods.

Average SWC distribution with depth from window periods during November, December and January are illustrated in Figure 4.6. Average daily ET_o and -daily irrigation was recorded to be 6.3mm and 1.73 mm respectively. In general, a gradient of decreasing SWC from the soil surface downwards was observed for all three treatments, a phenomenon familiar with drip irrigation (Bravdo and Proebsting, 1993). An exception occurred in T3-1.6L.h^{-1} which had lower SWC at 15 cm compared to 30 cm, an observation recorded by Pijl (2001) as well under 1.6 L.h^{-1} discharge rate drippers. T1-0.4L.h^{-1} also showed a rise in SWC at 80 cm depth deviating from the general decreasing trend. It is not certain if this rise in SWC at 80 cm is due to an irrigation effect, because SWC remained moist at this depth throughout the season with little to no fluctuation following irrigation and similar lower SWC at 60 cm for all three treatments.

The main effect on irrigation depth and the effect of discharge rate on SWC distribution within the soil profile can be observed in the upper 45 cm of the profile (active root zone) with different SWC values at 15cm, 30 cm, and 45 cm for all three treatments. At 15 cm depth, SWC differed significantly between all three treatments with highest SWC associated with T1-0.4L.h^{-1}, followed by T2-0.7L.h^{-1} and T3-1.6L.h^{-1} respectively (0.257 - above FC, 0.192 and 0.112 $cm^3.cm^{-3}$). Thus, applying water at a very low discharge rate continuously maintains a higher SWC (above FC) closer to the soil surface and decreases as discharge rate increases. At 30 and 45 cm the same trend was observed in SWC distribution with SWC decreasing with increase in discharge rate. This trend may be due to long redistribution times as discharge rate increases. Applying the same volume of water with different discharge rates results in different irrigation durations, allowing longer redistribution time as irrigation is shorter causing average SWC at the point of measurements (sensors) to be lower at the various depths. This trend also may reflect the differences in the shape of the wetted soil volume with each treatment indicating that the irrigation volume in T1-0.4L.h^{-1} might be smaller and narrower, hence an average higher SWC in the upper 45 cm, followed by T2-0.7L.h^{-1} with a slight wider distribution and T3-1.6L.h^{-1} reflecting shallow and wider water distribution. SWC at FC was recorded under T1-0.4L.h (0.2 $cm^3.cm^{-3}$) at 30 cm.

No significant difference in SWC was recorded at 60 cm between treatments with SWC at 0.04 $cm^3.cm^{-3}$, a SWC value below – 100 kPa for this soil. This would imply that the depth of the wetted bulb and irrigation depth for all three treatments is somewhere between 45 and 60 cm during these high-water demanding periods. This is a desired irrigation depth as the main root mass for citrus trees is usually found within the upper third to two thirds of the depth of the deepest roots (Khedkar, 2015), often equal to around 60 cm. Thus, for all three treatments a zone of EAW up to 45 cm depth was maintained during high evaporative demanding periods with significantly higher SWC (at FC, 0.2 $cm^3.cm^{-3}$) in the ARZ in T1-0.4L.h^{-1} compared to T2-0.7L.h^{-1} and T3-1.6L.h^{-1} with water contents of 0.16 $cm^3.cm^{-3}$ (above 50% EAW) and 0.12 $cm^3.cm^{-3}$ (between 50% EAW and EAW) respectively (Figure 4.7). Relatively low SWC was recorded in the LRZ for all three treatments equal to -100 kPa for T1-0.4L. h^{-1} and below -100 kPa for T2-0.7L.h^{-1} and T3-1.6L.h^{-1} with no significant difference between the treatments (Figure 4.8). SWC remained very consistent at all depths of measurement during December and January (Figure 4.3 a and b) for all three treatments.

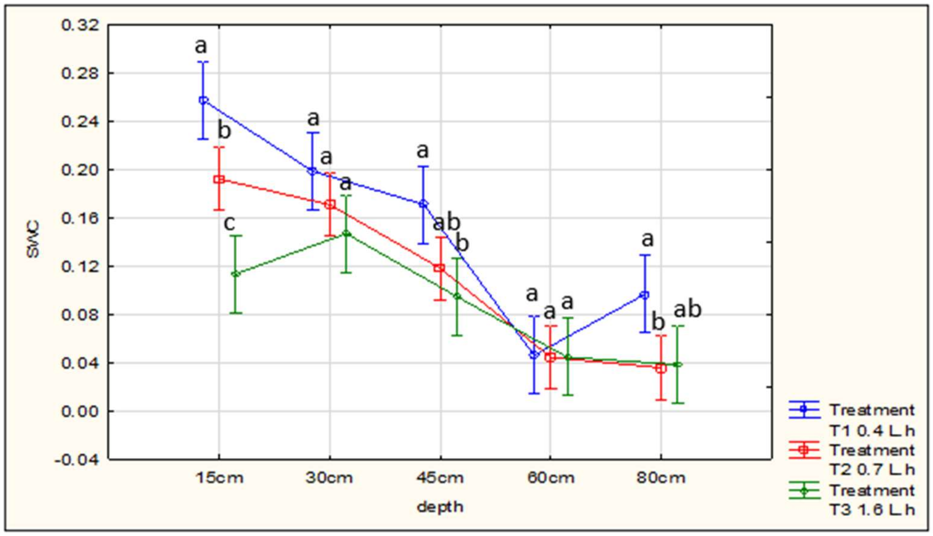

Figure 4.6: Average θv SWC distribution with depth under a dripper during high evaporative demanding months. Treatment means with different letters within a column differ significantly (*p* ≤ 0.005). Vertical bars denote ± SE.

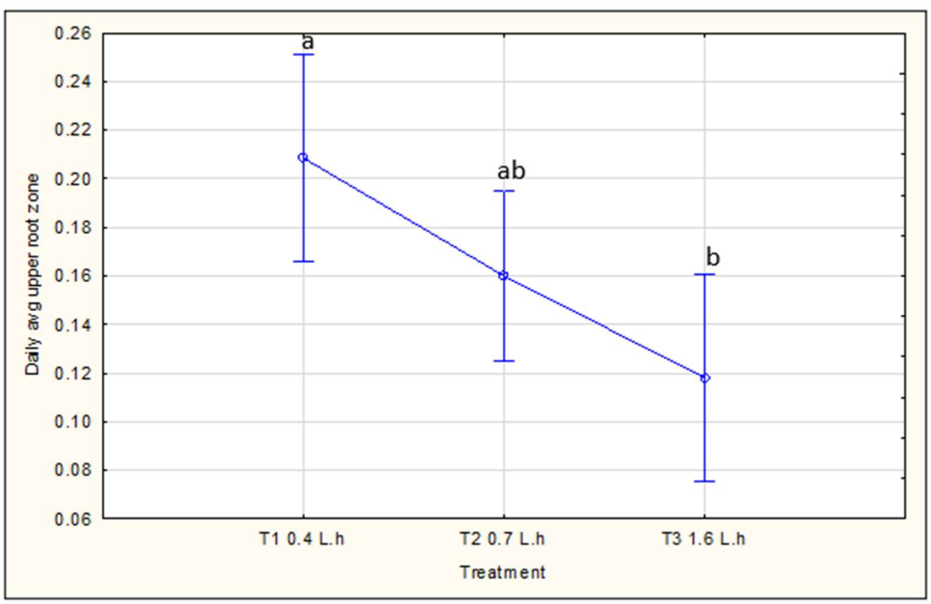

Figure 4.7: Average volumetric soil water content in the active root zone (ARZ) during high evaporative demanding months. Treatment means with different letters between columns differ significantly (*p* ≤ 0.005). Vertical bars denote ± SE.

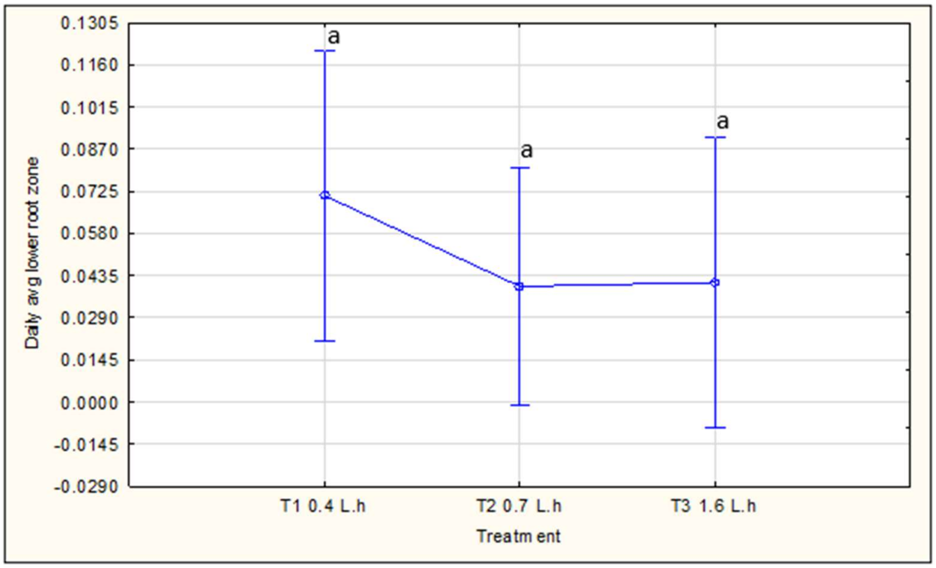

Figure 4.8: Average volumetric soil water content in the lower root zone (LRZ) during high evaporative demanding months. Treatment means with different letters between columns differ significantly ($p \leq 0.005$). Vertical bars denote ± SE.

4.2.4 Diurnal SWC fluctuation

Three continuous irrigation durations resulting from three treatments of drip discharge rates showed different fluctuation in SWC over time. The relationship between fluctuation in volumetric SWC and hour of the day on the 29th of January 2020 are illustrated in Figure 4.9. (ET_o of 6 mm was recorded on this day with max and min temperature of 30.7°C and 16.3°C respectively. Applying the same volume of water per treatment resulted in 10 hours and 30 min continuous irrigation for T1-0.4L.h^{-1} starting at 04:30 AM, 6 hours for T2-0.7L.h^{-1} and 1-hour 20min for T3-1.6L.h^{-1} , both starting at 09:00 AM. This resulted in 17.68 $m^3.ha^{-1}$ applied per treatment equal to 22 L per tree for a 5 x 2.5 m spacing (4.2 L per dripper at the position of measurements but 2.1 L for T3-1.6L. h^{-1} due to 50 cm spacing between drippers).

The effect on SWC due to drip treatments are most noticeable at 15 and 30 cm depths showing an increase in SWC under all three treatments during irrigation events. When irrigation commenced at 04:30 AM for T1-0.4L.h^{-1}, SWC began to rise gradually at 15 cm depth reaching a plateau after four and a half hours of irrigation whereafter SWC remained constant at 0.27 $cm^3.cm^{-3}$ for the remaining of the irrigation event until 15:00 PM. Maximum SWC at 15cm for T1-0.4L.h^{-1} was already reached at 09:00 AM when irrigation only started for T2-0.7L.h^{-1} and T3-1.6L.h^{-1} and thereafter decreasing gradually to 0.241 $cm^3.cm^{-3}$ the next morning when irrigation started again at 04:30 AM. T2-0.7L.h^{-1} also showed a gradual rise in SWC and reached a maximum of 0.247 $cm^3.cm^{-3}$, also four and a half hours after irrigation commenced and remained constant until 15:00 PM and decreased gradually to 0.178 $cm^3.cm^{-3}$ the next morning before irrigation started again. T3-1.6L.h^{-1} showed a sharper incline in SWC and reached maximum SWC at 0.128 $cm^3.cm^{-3}$, an hour and a half later at the end of the irrigation event. Field capacity (FC) was not reached in T3-1.6L.h^{-1} .

At 30 cm T1-0.4L.h^{-1} and T2-0.7L.h^{-1} shows the same SWC distribution over time until 07:30 AM when an increase is observed in T1-0.4L.h^{-1} indicating the advancement of the waterfront three hours after irrigation started and a decline in SWC under T2-0.7L.h^{-1}. This indicates water being extracted at 30 cm under T2-0.7L.h^{-1} before the waterfront has reached this depth. An increase in SWC is observed at 11:30 AM, showing the advancement of the wetting front under T2-0.7L.h^{-1} at 30 cm, an hour and a half after irrigation started. SWC increased steadily reaching a maximum at 0.214 $cm^3.cm^{-3}$, slightly above T1-0.4L.h^{-1} at 15:30 PM whereafter the same SWC is observed under T1-0.4L.h^{-1} and T2-0.7L.h^{-1} until the next day which follows the same pattern. T3-1.6L.h^{-1} showed an increase in SWC at 10:00 AM reaching a maximum at 11:00, when T2-0.7L.h^{-1} showed the lowest SWC for the day. At 45 cm no fluctuation was observed under T1-0.4L.h^{-1} but showed constant and highest SWC during the day. A slight fluctuation in SWC is observed in T2-0.7L.h^{-1}, reaching a minimum at 16:00 PM and rising steadily towards the next morning as well as T3-1.6L.h^{-1} reaching a maximum at 14:30 as the wetted soil volume shrunk and expanded during the day. At 60 and 80 cm no daily fluctuation was observed remaining constant at low SWC, indicating the periphery of the wetted soil volumes somewhere between 45 and 60 cm and water content below the active root zone not available for rapid uptake. This agrees with graphs generated by Pijl (2002) of daily water fluctuation in the root zone under drip irrigation.

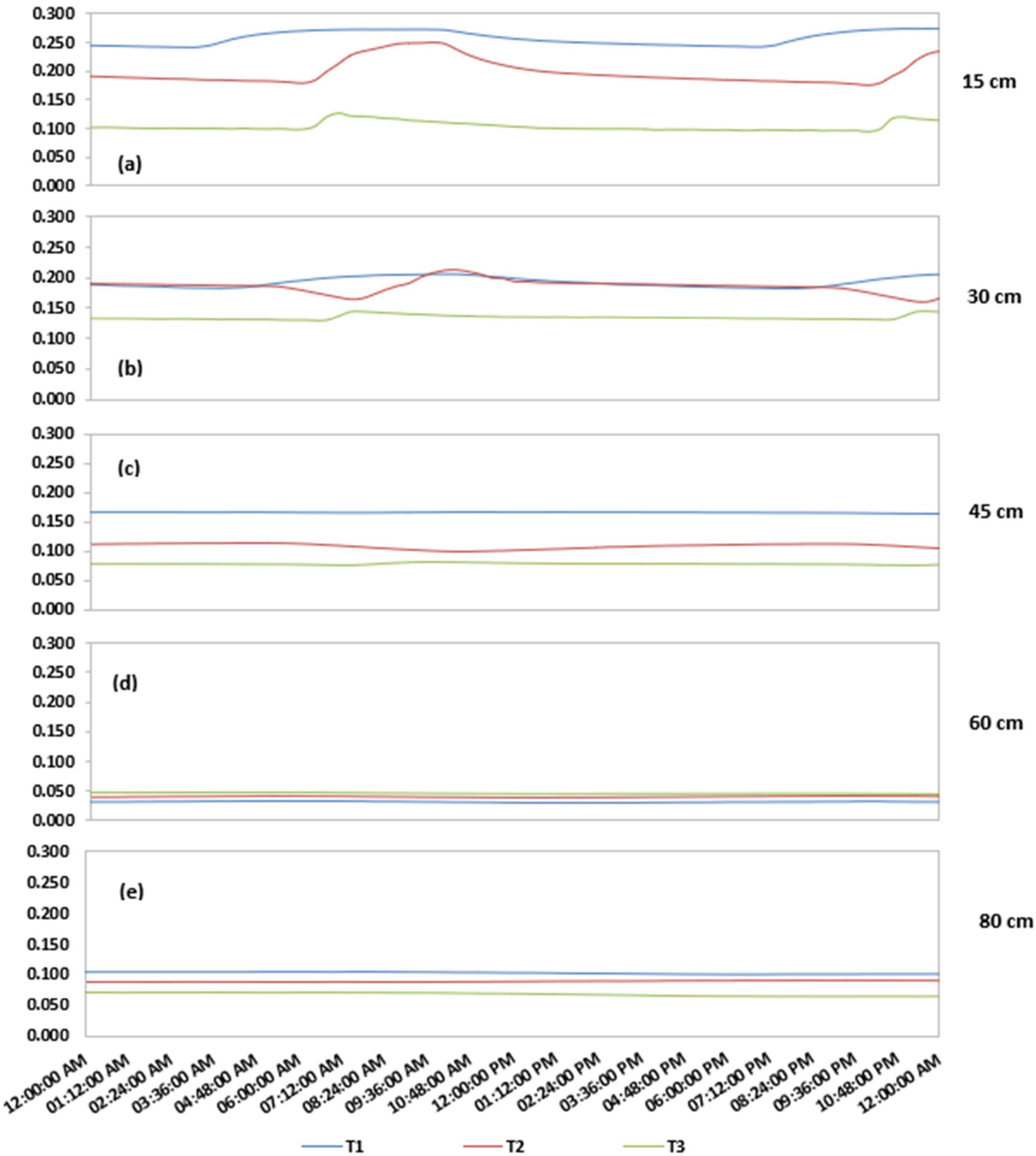

Figure 4.9: Dynamics of soil water content in the soil profile at 15cm (a), 30cm (b), 45cm (c), 60cm (d) and 80 cm (e) depths for three treatments of drip irrigation T1- 0.4 L.h^{-1}; T2- 0.7 L. h^{-1}; T3- 1.6L.h^{-1} discharge rate, on the 29th of January 2020. ETo was 6 mm.

4.2.5 2-Dimensional water distribution

Spatial water distribution under a dripper was measured on the 19th of October and 28th of December 2020 when water demand was high. 2-Dimensional water distribution patterns during these days are illustrated in Figures 4.12 to 4.15. Reference evapotranspiration (ET_o) on the 19th of October and 28th of December were 4.79 and 7.29 mm respectively. Hourly ET_o on the respective days followed a typical bell shape as depicted in Figure 4.10. Irrigation hours for the different treatments on the separate days were as follow: 19 October: T1-0.4L.h^{-1} 8 hours and 45 min, T2-0.7L.h^{-1} 5 hours and T3-1.6L.h^{-1} 1 hour and 5 min, resulting in 14m^3/ha (3.5 L /dripper for T1-0.4L.h and T2-0.7L.h and 1.75L/dripper for T3-1/6L.h), 28 December: T1-0.4L.h^{-1} 14 hours T2-0.7L.h^{-1} 8hours and T3-1.6L.h^{-1} 1hour 45 min resulting in 22m3/ha (5.6 L/dripper for T1-0.4L.h^{-1} and T2-0.7L.h^{-1} and 2.8 L/dripper for T3-1.6L.h^{-1}). Dripper position in relation to tree position and measurements are illustrated in Figure 4.11. Negative values indicate measuring points to the left of the start point of measurements.

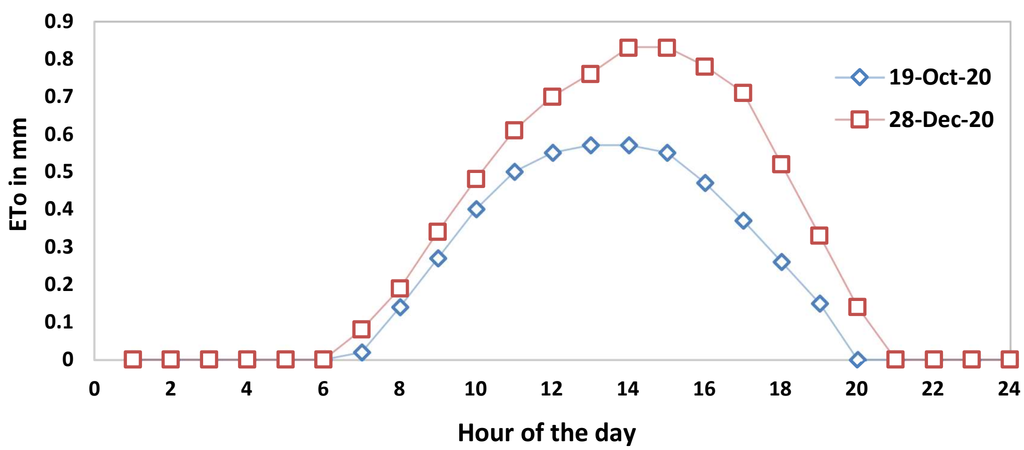

Figure 4.10: Hourly reference evapotranspiration (ET_o) generated from a nearby weather station on the 19th of October 2020 and the 28th of December 2020. Total ET_o was 4.79 mm and 7.29 mm for each day respectively

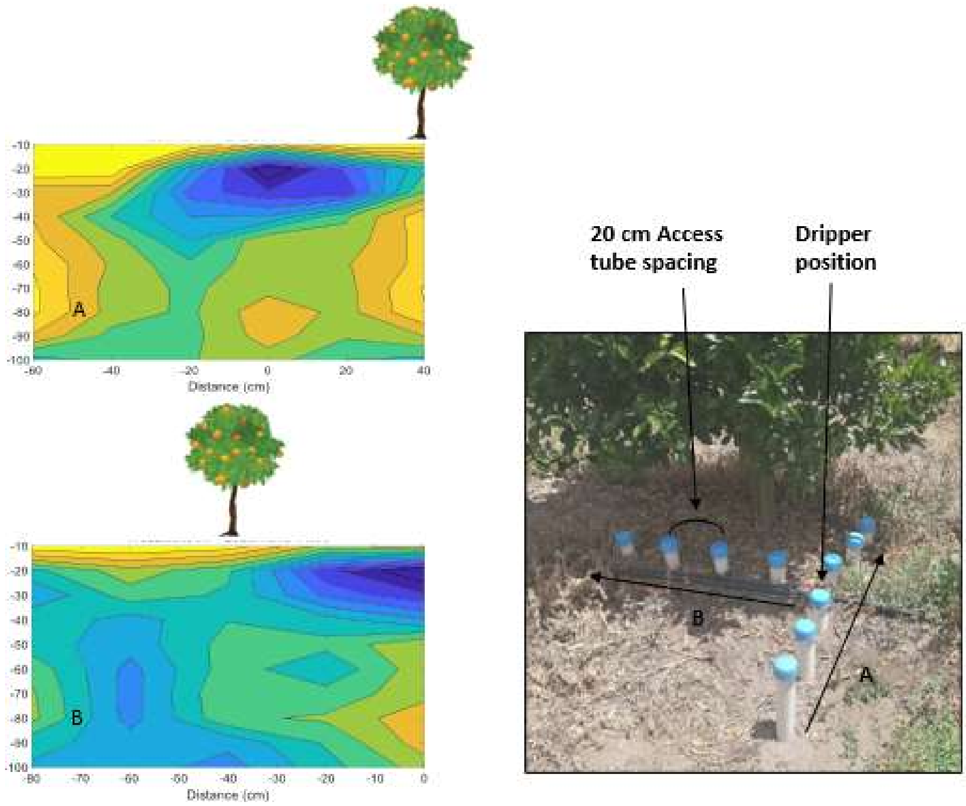

Figure 4.11 (Left): Representation of dripper position in relation to the tree for spatial water distribution measurements to visualize 2-D water distribution patterns across the ridge (A) and parallel to the ridge (B). Tree position are in line with the 40 cm access tubes as in Figure A and B, and dripper position was at 0 cm. Negative values are left from the dripper. (Right): Layout of the access tubes parallel and across the ridge for soil moisture measurements in relation to the tee position

4.2.5.1 Wetted soil volume dimensions

Irrigation event of 19 October 2020

On the 19th of October 2020 a shorter irrigation event took place due to a lower evaporative demand (Figure 4.10) as described earlier. Irrigation started at 05:15 for T1-0.4L.h^{-1} and continued until 14:00, T2-0.7L.h^{-1} started at 09:00 and stopped at 14:00, T3-1.6L.h^{-1} also started at 09:00 but stopped at 10:05. By inspection of the graphical presentation of the wetted soil volumes with each irrigation treatment, it is evident that each irrigation treatment resulted in a different pattern of spatial water distribution across the ridge and parallel with the ridge.

Across the ridge: Applying the daily water requirement at a very low rate (T1-0.4L.h^{-1}) resulted in the wetted soil volume moving towards the inside of the ridge (Figure 4.12 a and Figure 4.12 b (1a-1f)) and dryer soil is observed on the outside of the ridge. This may be due to several factors: more water extraction by plant roots more to the outside of the ridge, greater evaporation from this exposed area of the ridge or preferential flow towards the inside of the ridge due to more rocks or disturbance of the profile during installation of the access tubes. T2-0.7L.h^{-1} Resulted in a wetted soil volume moving more towards the outside of the ridge (Figure 4.12 a and Figure 4.12 b (2a-2f)) and may be due to higher extraction by plant roots from the inside of the ridge or also just preferential flow toward the outside of the ridge as the ridge in general promote water drainage out of the root zone. The same trend is observed with T3-1.6L.h^{-1}, and a higher discharge rate resulted in more water moving towards the outside of the ridge and a drier profile can be observed in the middle of the ridge (Figure 4.12 a and Figure 4.12 b (3a-3f)). Preferential flow due to rocks and soil disturbance during access tube installation is also likely.

By observing the spatial water distribution of T1-0.4L.h^{-1} at 16:00 (Figure 4.12 b (1f)), when irrigation for all treatments have ceased and some redistribution has occurred, lateral water distribution of the main core of the wetted soil volume (in the upper 50cm of the soil profile) did not exceed 30 cm to the outside of the ridge and 40 cm to the inside of the ridge. This refers to the contour line of the green colour, equal to a SWC of 0.07 $cm^3.cm^{-3}$. Lateral water distribution with T2-0.7L.h^{-1} (Figure 4.12 b (2f)), did not exceed 55cm to the outside of the ridge and distributed beyond 40 cm to the inside of the ridge. A wide lateral distribution of water is observed with T3-1.6L.h^{-1} and water moved beyond 60cm to the outside of the ridge and up to 40 cm to the middle of the ridge (Figure 4.12 b (3f)). Thus, increase in later water distribution is observed with increase in discharge rate under orchards conditions. Vertical water distribution at 16:00 was up to 100cm in all three treatments, by observing the green contour line (0.07 $cm^3.cm^{-3}$) with high soil moisture observed in the subsoil compared to the upper soil profile with T3-1.6L.h^{-1}. The main core of the wetted soil volume was up to 45, 55 and 30 cm in depth for T1-0.4L.h^{-1}, T2-0.7L.h^{-1} and T3-1.6L.h^{-1} respectively at 16:00 (Figure 4.12 b).

Parallel with the ridge: Water movement parallel with the drip line also resulted in different distribution patterns per treatment. Lateral movement of the core of the wetted soil volume with T1-0.4L.h was up to 40 cm away from the dripper at 16:00 (Figure 4.13 b (1f)). Vertical distribution was mainly to 50 cm although water is observed beyond this depth up to 100 cm, directly below the dripper. T2-0.7L.h^{-1} Resulted in a wider distribution of water and merging of the wetted soil volumes from adjacent drippers occurred, indicated by the blue contours in the middle of the profile up to 100 cm (Figure 4.13 b (2f)). Merging of wetted soil volumes often results in water moving beyond the active root zone as more downward water movement occurs where wetted soil volumes meet (Rui *et al.*, 2012). They reported that as the wetted bulb expands, points source infiltration pattern transforms to a line source infiltration, increasing the amount of water distributed vertically rapidly. Observing water distribution at 12:00, merging of the wetted soil volumes in T2-0.7L.h^{-1} is mainly at 30 cm below the soil surface (Figure 4.13 b (2d)). The higher discharge rate and shorter spacing (50 cm) of drippers in T3-1.6L.h^{-1} resulted in a wetted strip mainly in the upper 40 cm of the soil profile (Figure 4.13 a and Figure 4.13 b). Preferential flow occurred at one of the access tubes (position-20 cm) and water was observed up to 100cm down the profile.

Irrigation event of 28 December 2020

On the 28th of December 2020 a long irrigation event took place due to high evaporative demand (Figure 4.10). Irrigation started at 05:00 in T1-0.4L.h^{-1} and continued until 19:00, T2-0.7L.h^{-1} started at 09:00 and stopped at 17:00, T3-1.6L.h^{-1} also started at 09:00 but stopped at 10:45.

Across the ridge: Similar patterns in the wetted soil volume distribution with each treatment were observed as on the 19th of October although a more prominent wetted soil volume was observed with each treatment, especially T1-0.4L.h^{-1} and T2-0.7L.h^{-1}, due to the rest of the soil drying out with less rain and average higher temperatures in December. Lateral distribution across the ridge was limited to 30 cm to the outside and 35 cm towards the inside of the ridge in T1-0.4L.h^{-1} (Figure 4.14 a and 4.14 b (1a-1f)). Vertical distribution was up to 55 cm. T2-0.7L.h^{-1} Resulted in water distribution up to 30 cm to the outside of the ridge and beyond 40 cm to middle of the ridge, away from the emitter (Figure 4.14 a and 4.14 b (2a-2f)). A deeper vertical distribution was observed compared to T1-0.4L.h^{-1} and was mainly up to 65 cm (Figure 4.14 b (2d)). Greater later distribution was again observed with T3-1.6L.h^{-1} than T1-0.4L.h^{-1} and T2-0.7L.h^{-1} and distribution was up to 45 cm to the outside of the ridge and beyond 40 cm towards the middle away from the emitter, resulting in wetted soil volumes merging to form a wetted strip (Figure 4.14 a and 4.14 b (3a-3f)).

Parallel with the ridge wetted soil volumes from both T2-0.7L.h^{-1} (Figure 4.15 a and Figure 4.15 b (2a-2f)) and T3-1.6L.h^{-1} (Figure 4.15 a and Figure 4.15 b (3a-3f)) again merged as on the 19th of October. T1-0.4L.h^{-1} Resulted in less horizontal distribution characterized by a smaller irrigation volume than T2-0.7L.h^{-1} only 40 cm away from the dripper (Figure 4.15 a and Figure 4.15b(1a-1f)). Vertical distribution of the main wetted soil volume was up to 45 cm. Two-dimensional water distribution in a study by Pijl (2001) showed up 45 cm horizontal and beyond 50 cm vertical water distribution with 1.6L.h drippers, one dripper per tree on a coarse sand. Thus, applying daily water equipment via ultra-low flow drip irrigation (T1-0.4L.h^{-1}) allow for adequate soil water distribution to support tree growth while maintaining high SWC in the active root zone.

4.2.5.2 Wetted soil volume dynamics

When a different amount of water was applied on the two separate days of measurements in October and December due to different climatic conditions, different trends in the fluctuation of the wetted soil volumes were observed although the overall shape of the wetted soil volume per treatment remained the same.

Observing soil water distribution across the ridge on the 19th of October at 07:00 in the morning for all three treatments, it seems as if a bimodal distribution of water content exists, characterized by a main wetted soil volume in the upper 50 cm and concentrated areas of higher soil water content in the lower 50 cm (Figure 4.12 a and Figure 4.12 b (1a,2a and 3a)). At 09:00 an increase in SWC is observed in the main core of the wetted soil volume in T1-0.4L.h^{-1} (Figure 4.12a (1b)) with a slight decrease observed in the lower root zone by shrinkage of wet zones. With T2-0.7L.h^{-1}, a shrinkage of the core of the wetted soil volume was observed as water was being used and irrigation only started (Figure 4.12 a (2b)). This corelates with Figure 4.9 (b) at 30 cm as a decrease in SWC was observed during this time of the day as explained in section 4.2.4. At 10:00 and 12:00 an interesting water distribution pattern was observed in both T1-0.4L.h^{-1} and T2-0.7L.h^{-1}. As the core of the wetted soil volume increased in SWC (larger dark blue area) a very uniform soil water content distribution was observed in the rest of the profile, characterized by the yellow-brownish colour with a SWC of 0.05 $cm^3.cm^{-3}$ (Figure 4.12 a (1c,2c)) and Figure 4.12 b (1d,2d)). Thus, applying the water at a low rate resulted in an increase of water content in the main wetted soil volume as ET_o rate increased (Figure 4.9), but redistribution of water in the lower root zone, observed visually as 'drier' compared to earlier in the morning. At 10:00 and 12:00 a great contrast existed between the main wetted soil volume and the rest of the soil profile, indicated by the contour line separating SWC of 0.12 and 0.05 $cm^3.cm^{-3}$.

At 14:00 the soil water distribution pattern changes and is similar to what was observed early in the morning, with more gradients of SWC, shrinkage of the core of the wetted soil volume and water moving below 50 cm shown by zones of higher SWC in the lower root zone (Figure 4.12 b (1e,2e)). From 14:00 to 16:00 the water distribution did not fluctuate that much and only a slight reduction in SWC is observed in the core of the wetted soil volume in both T1-0.4L.h^{-1} and T2-0.7L.h^{-1} (Figure 4.12 b (1f,2f)).

Throughout the day almost no fluctuation in the wetted soil volume associated with T3-1.6L.h^{-1} was observed, only a slight shrinkage occurred from 07:00 to 09:00 when the tree started using water and irrigation has not yet started. This shrinkage was observed at the outer part of the ridge (Figure 4.12 a (3a-3b)).

Similar trends in the fluctuation of the wetted soil volumes during the day were observed in the parallel with the ridge section. More gradients of SWC in the wetted soil volume earlier in the day (07:00 and 09:00) and a visually 'wetter' soil profile for T1-0.4L.h^{-1} and T2-0.7L.h^{-1} (Figure 4.13 a (1a-1b,2a-2b)). As the day proceeds and ET_o rate increases, the core of the wetted soil volume increase in SWC (larger blue area) with the rest of the profile portraying visually 'drier' at noon (Figure 4.13 b (1d,2d)). At 14:00 and 16:00, redistribution occurred resulting in visually 'wetter' soil profiles characterized by more blue and green colours (Figure 4.13 b (1e-1f,2e-2f)). In T3-1.6L.h^{-1} the development of the wetted soil volumes can be seen from 07:00 until 10:00 (Figure 4.13 a (3a-3c)) when wetted soil volumes merge forming a continuous wetted strip, remaining until 16:00 (Figure 4.13 b (3f)).

On the 28th of December when higher total ET_o was recorded and the soil profile was overall drier due to less rain and warmer climate, the spatial soil water distribution looked different. Observing the cross section of the ridge (Figure 4.14 a and 4.14 b) as water was applied continuously in different durations per treatment, the core of the wetted soil volume increased in SWC in both T1-0.4L.h^{-1} and T2-0.7L.h^{-1} but irrigation depth and horizontal distribution did not fluctuate. This shows that applying water at a low rate maintains steady high SWC in the ARZ, reducing fluctuation, agreeing with findings from Assouline (2002) and Segal *et al*. (2006). Only at 18:00 when irrigation in T2-0.7L.h^{-1} had stopped did redistribution occur and more gradients in water content is observed (Figure 4.14 b (2e)). Thus, while water was applied in T2-0.7L.h^{-1} and ET_o was high, the wetting front did not move beyond 70 cm, but when ET_o rate declined dramatically at 18:00 (Figure 4.10) and the water demand was low, water redistributed and moved beyond 70 cm.

Applying water at a very low rate as with T1-0.4L.h^{-1} the wetted soil volume remained in the upper 55 cm and at 18:00 when tree water demand was low and irrigation was still on, the wetting front still did not exceed 55 cm. Thus, as water was applied and water demand varied during the day as seen with the bell shape curve of hourly ET_o, the wetted soil volume remained in the upper soil profile and only the main core increased in SWC as irrigation continued. Only a slight fluctuation was observed with T3-1.6L.h^{-1} seen in the expansion of the wetted soil volume towards the outside of the ridge with time (Figure 4.14 a (3a-3c)) and shrinkage observed at 19:00 (Figure 4.14 b (3e)). Although the spatial water distribution was different in the parallel with the ridge section, the trend was the same as with the cross section of the ridge, characterized by a main wetted core with slight merging in T1-0.4L.h^{-1} (the brownish colour) (Figure 4.15 a and b (1a-1e)) and greater merging in T2-0.7L.h^{-1} forming a wetted strip (Figure 4.15 a and b (2a-2e)) and redistribution occurring at 18:00 (Figure 4.15 b (2e)). Again, a wetted strip was formed with T3-1.6L.h^{-1} and slight fluctuation observed under the dripper with increase in the wetted soil volumes until 14:00 (Figure 4.14 a (3a-3c))and shrinkage thereafter (Figure 4.14 b (3d-3e)).

When observing values in mm for each profile in each treatment over time compared with the ET_o trend only little variation in SWC is observed (Figure 4.16). Most daily fluctuation is seen in the ARZ whereas the SWC in the LRZ stays fairly constant throughout the day on both days of measurements. Thus, even if a long or short irrigation is applied varying with the climatic demand, excess water is not moving beyond the root zone but remains constant, implying that the application rate is close to water consumption rate. On the 19th of October T2-0.7L.h^{-1} initially show a decrease in the ARZ across the ridge and parallel with the ridge as water is being used and then increase as irrigation is applied (Figure 4.16 b and e). Overall, all three treatments show a trend of highest SWC during midday when ET_o is highest, attributed to the increase in SWC in the core of the wetted soil volume, and lowest in morning and afternoon. On 28th of December the cross section with the ridge shows constant SWC during the day in both the ARZ and LRZ for all tree treatments (Figure 4.16 h-i). In the parallel section with the ridge, SWC was highest during midday for both T2-0.7L.h^{-1} and T3-1.6L.h^{-1} but lowest during midday in T1-0.4L.h^{-1}, observed in the profile total (Figure 4.16(j)) and the ARZ (Figures 4.16 (k)). The slight decrease in midday would then imply that during midday the rate of water supply is less than the demand and resulting a decrease in SWC. As ET_o rate decrease SWC increase again, implying that application rate is greater than the demand. Schoeman suggested early irrigations so that morning conditions could be optimized to ensure that plants perform optimally at the time of highest photosynthetic activity (Schoeman, 2002).

4.3 Conclusion

The limiting factors that determine the spacing of drippers, number of emitters and drip lines, frequency of irrigation and subsequently the cost is the horizontal spreading of water and the volume of soil wetted (Skaggs, Trout and Rothfuss, 2010).

Applying the seasonal water requirements of 4-year-old 'Nadorcott' mandarin trees planted in a sandy soil with three different discharge rate emitters resulted in different water distribution patterns in the soil profile and root environment. Ultra-low flow drip maintained an average higher SWC in the active root zone, measured under a dripper during the season followed by T2-0.7L.h^{-1} and T3-1.6L.h^{-1} respectively. The average lower SWC recorded with T3-1.6L.h^{-1} was expected due to narrower spacing of drippers and thus less water applied per dripper, at the point of measurement.

Throughout the season an average higher SWC was observed at 45 cm below the surface in T1-0.4L.h^{-1} followed by T1-0.7L.h^{-1} and T3-1.6L.h^{-1}. This result may be due to the average higher antecedent SWC when irrigation was applied again, increasing the soil water conductivity as less pore space in the vicinity of the dripper have to be filled with water (Fan *et al.*, 2018), resulting in deeper penetration of the main core of the wetted bulb in T1-0.4L.h^{-1} and least in T3-1.6L.h^{-1}

During high evaporative demanding months, significant differences in water distribution with depth with each treatment was observed closest to the drip line with significantly higher SWC under T1-0.4L.h^{-1} followed by T2-0.7L.h^{-1} and T3-1.6L.h^{-1} respectively at 15 cm depth. Overall average higher SWC was recorded in the ARZ under T1-0.4L.h^{-1} followed by T2-0.7L.h^{-1} and T3-1.6L.h^{-1} respectively during this period. Higher SWC in the LRZ was observed as well under T1-0.4L.h^{-1} with similar SWC in T2-0.7L.h^{-1} and T3-1.6L.h^{-1}. At 60 cm very similar SWC was observed in in all three treatments indicating the depth of irrigation and the periphery of the main wetted soil volume. This agrees with the effects of pulsing or continuous low application rate irrigation stated by Falivene (2005) i.e. maintaining the root zone SWC close to FC and bringing the main core of the wetted soil volume closer to the soil surface. This decrease in depth of the wetted soil volume is reported to reduce the movement of water past the root zone.

Diurnal fluctuation in SWC within and below the root zone indicated that low flow drip in general results in very little water fluctuation and SWC remains fairly constant. The most fluctuation was observed in the upper 30 cm in all three treatments with no fluctuation at 60 and 80 cm observed on a day basis. T2-0.7L.h^{-1} showed the most water extraction at 30 cm as irrigation started later in the day than T1-0.4L.h^{-1}, emphasizing the importance of scheduling and knowing the behaviour of water movement to match water demand with water supply.

Two-dimensional water distribution patterns parallel and across the ridge showed that T1-0.4L.h^{-1} resulted in a smaller wetted soil volume compared to T2-0.7L.h^{-1} with less horizonal and vertical water distribution from an emitter. More overlap was observed in T2-0.7L.h^{-1} parallel with the ridge resulting in greater vertical distribution of water between two adjacent drippers where wetted soil volumes merge. A wetted strip was formed under T3-1.6L.h^{-1} due to narrower spacing of drippers in the drip line compared to the wet 'pots' formed with T1-0.4L.h^{-1} and T2-0.7L.h^{-1}. Overall, very little fluctuation of the wetted soil volume was observed on a daily basis. However, a bimodal distribution of water was observed in T1-0.4L.h^{-1} and T2-0.7L.h^{-1} early in the morning when a shorter irrigation event took place characterized by a main wetted soil volume in the upper 50 cm and concentrated areas of higher soil water content in the lower 50 cm. Approaching midday as irrigation continued SWC in the main core of the wetted soil volume increased and lower SWC was observed in the rest of the soil profile indicating a 'shrinking' of the wetted bulb in the midday after which a bimodal water distribution resumed. T3-1.6L.h^{-1} showed verry little fluctuation during the day. When a longer irrigation event took place due to high evaporative demand a small prominent wetted bulb was observed with increase in SWC in the main core of the wetted soil volume as irrigation continued throughout the day with very little fluctuation noted. Only when irrigation stopped in T2-0.7L.h^{-1} and ET_o was negatable did redistribution take place and water moved past the active root zone into deeper soil layers. Again, very little fluctuation was noted in T3-1.6L.h^{-1}

Skaggs, Trout and Rothfuss (2010) mentioned that the goal is to maximize the relative horizontal to vertical water distribution for a given water application as increased vertical distribution is undesirable with water moving past the active root zone.

The study showed that applying water with low flow and ultra-low flow drip irrigation it is possible to maintain high SWC in the active root zone while applying water in long irrigation cycles allowing for sufficient horizontal spread and minimizing excessive vertical water distribution in a sandy soil. The wetted soil volumes noted with each treatment was sufficient to support tree growth and adequate root distribution. These observations can contribute to low flow drip irrigation management, dripper placement and irrigation scheduling calculations.

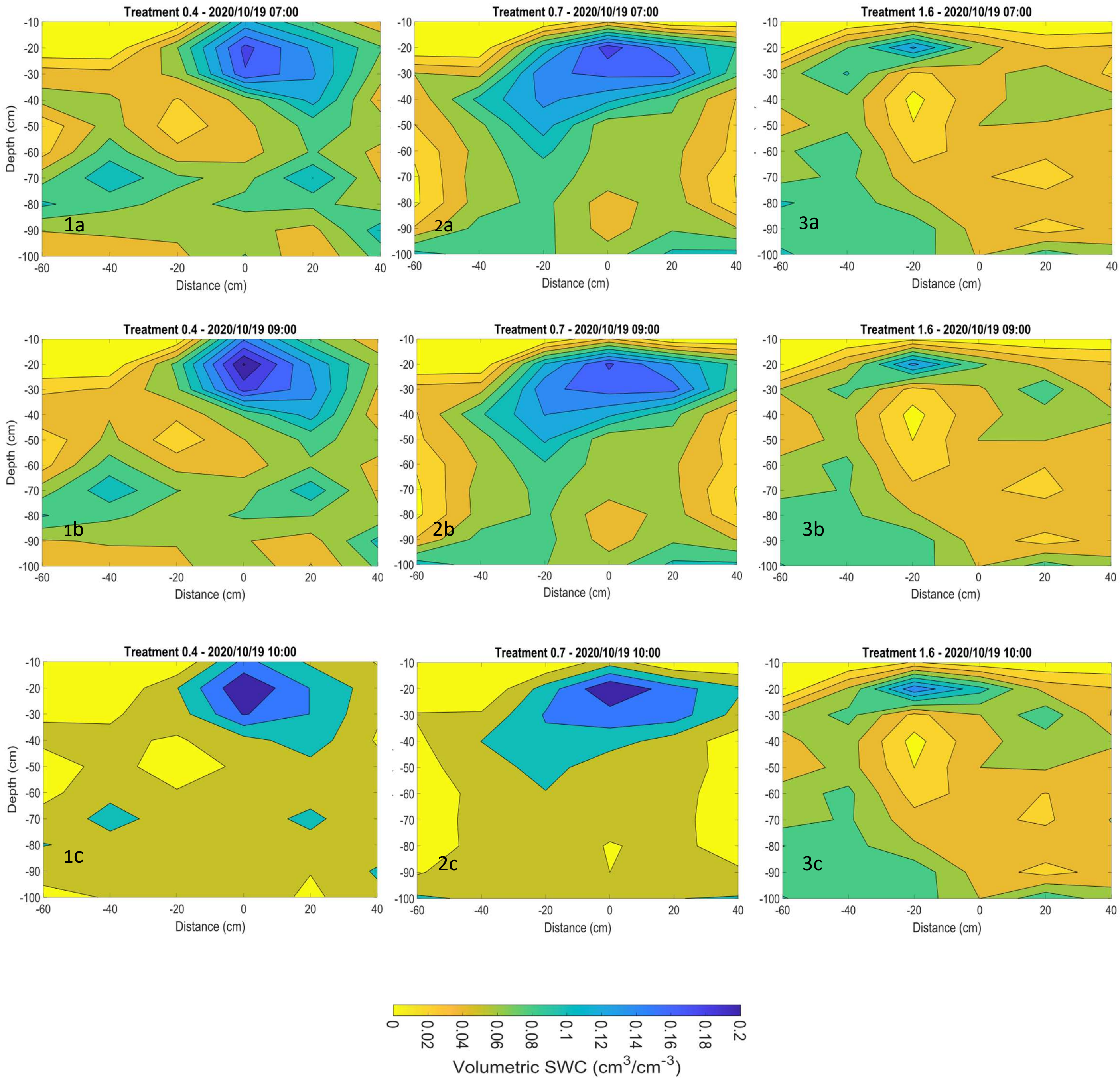

Figure 4.12 a: Spatial distribution of volumetric soil water content across the ridge for continuous drip irrigation with different treatments of drip discharge rate on the 19th of October 2021 at 07:00, 09:00 and 10:00 AM.

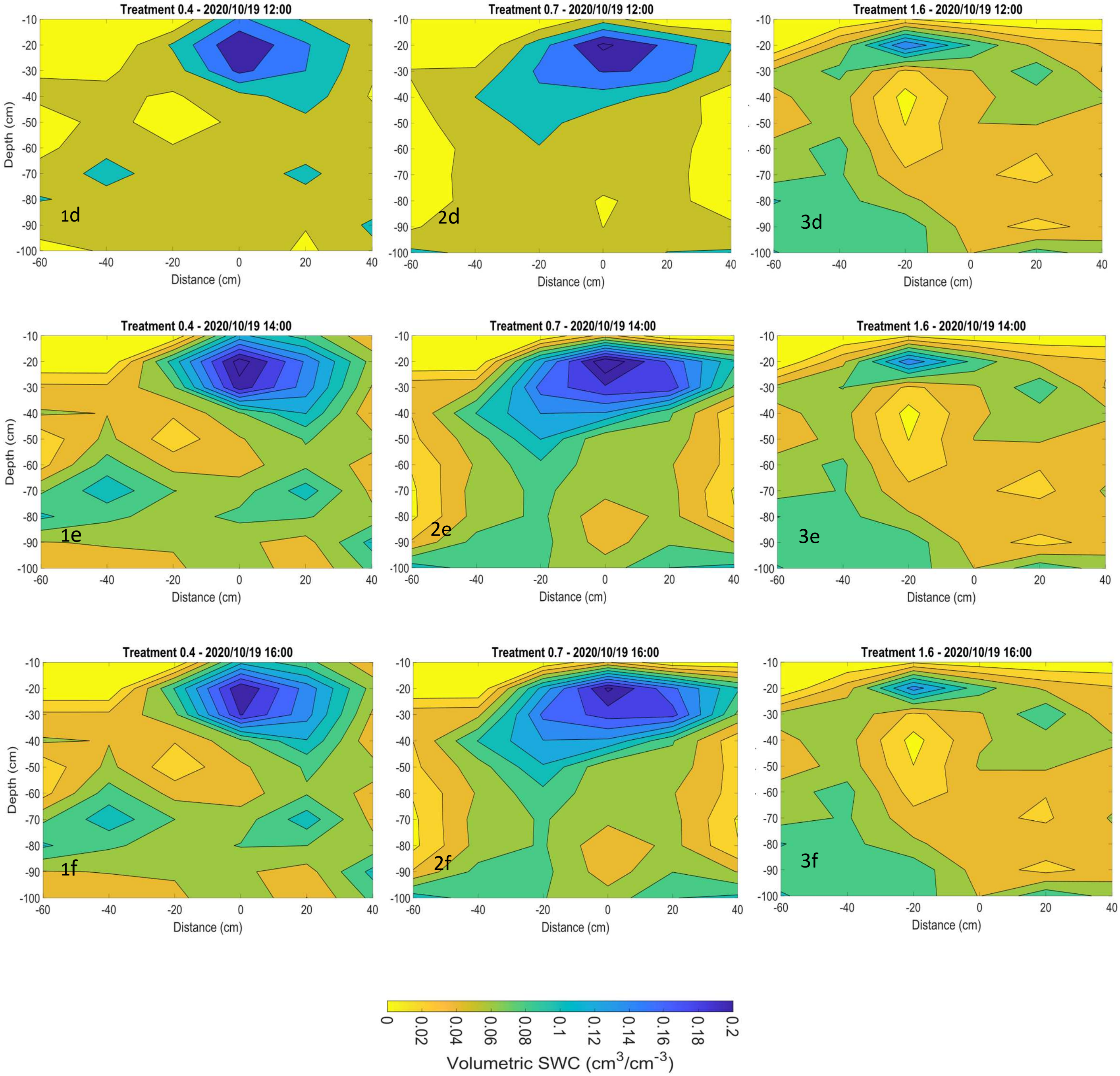

Figure 4.12 b: Spatial distribution of volumetric soil water content across the ridge for continuous drip irrigation with different treatments of drip discharge rate on the 19th of October 2021 at 12:00, 14:00 and 16:00 PM

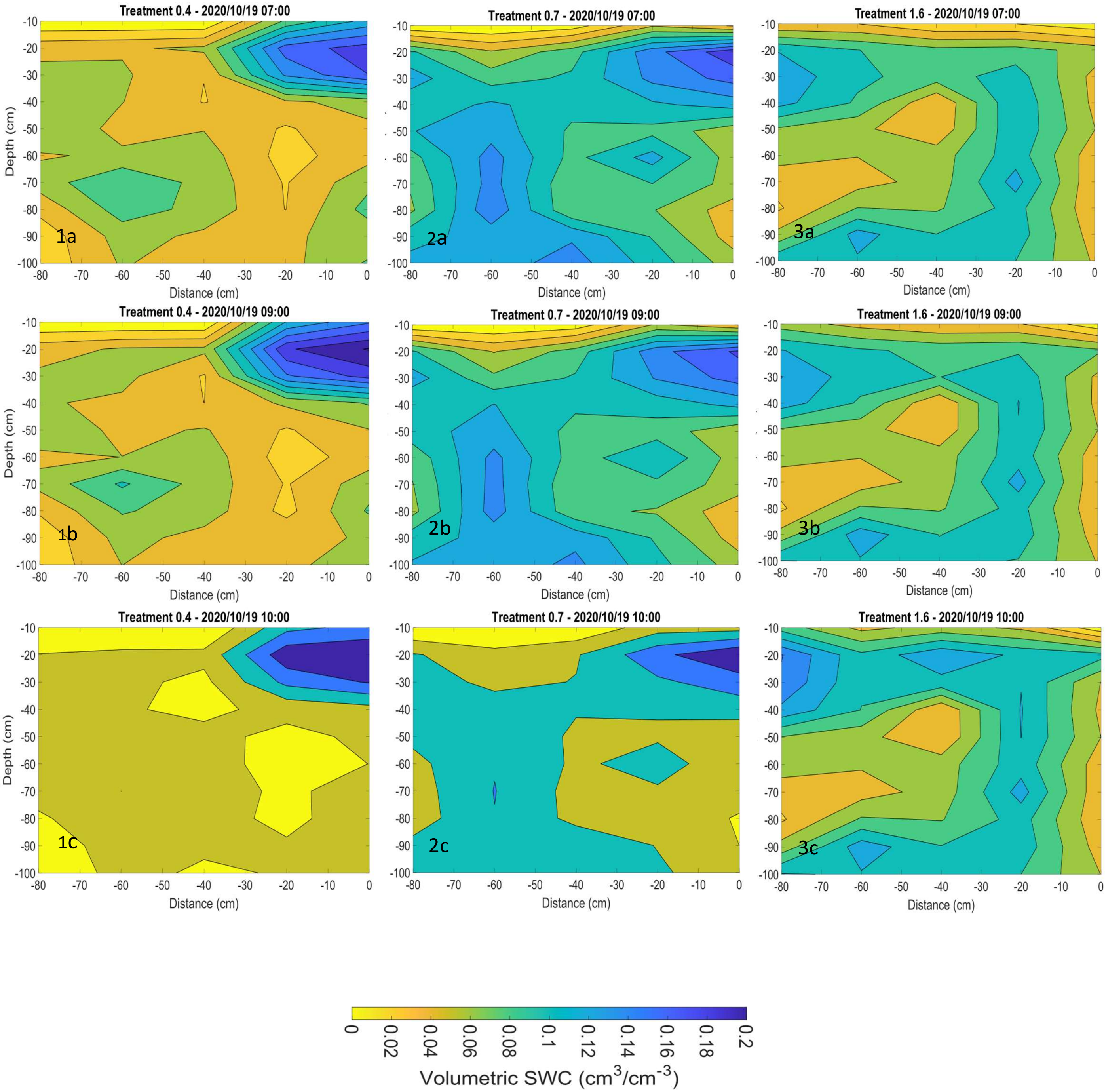

Figure 4.13 a: Spatial distribution of volumetric soil water content parallel with the ridge for continuous drip irrigation with different treatments of drip discharge rate on the 19th of October 2021 at 07:00, 09:00 and 10:00 AM.

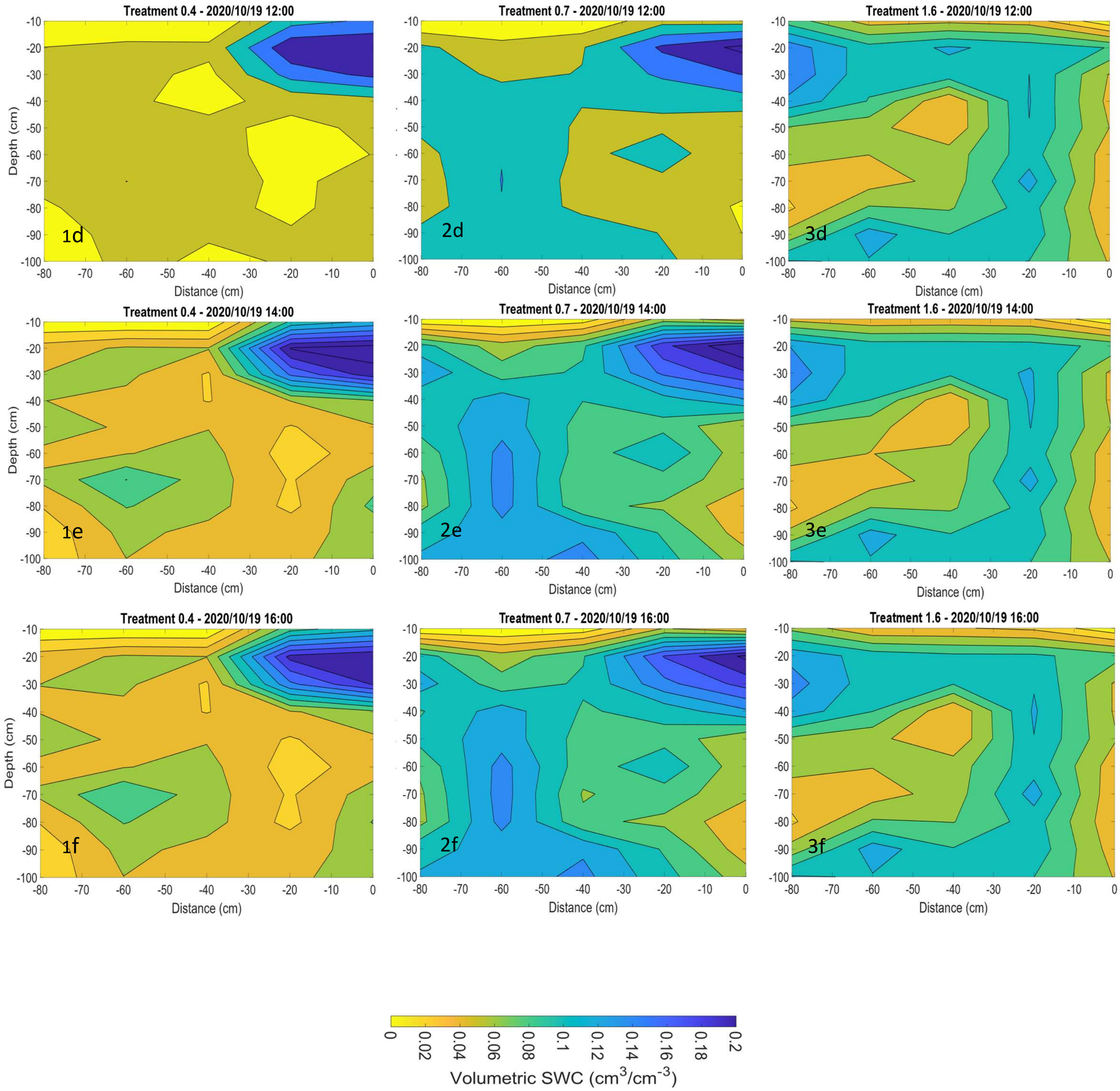

Figure 4.13 b: **Spatial distribution of volumetric soil water content parallel with the ridge for continuous drip irrigation with different treatments of drip discharge rate on the 19th of October 2021 at 12:00, 14:00 and 16:00 PM**

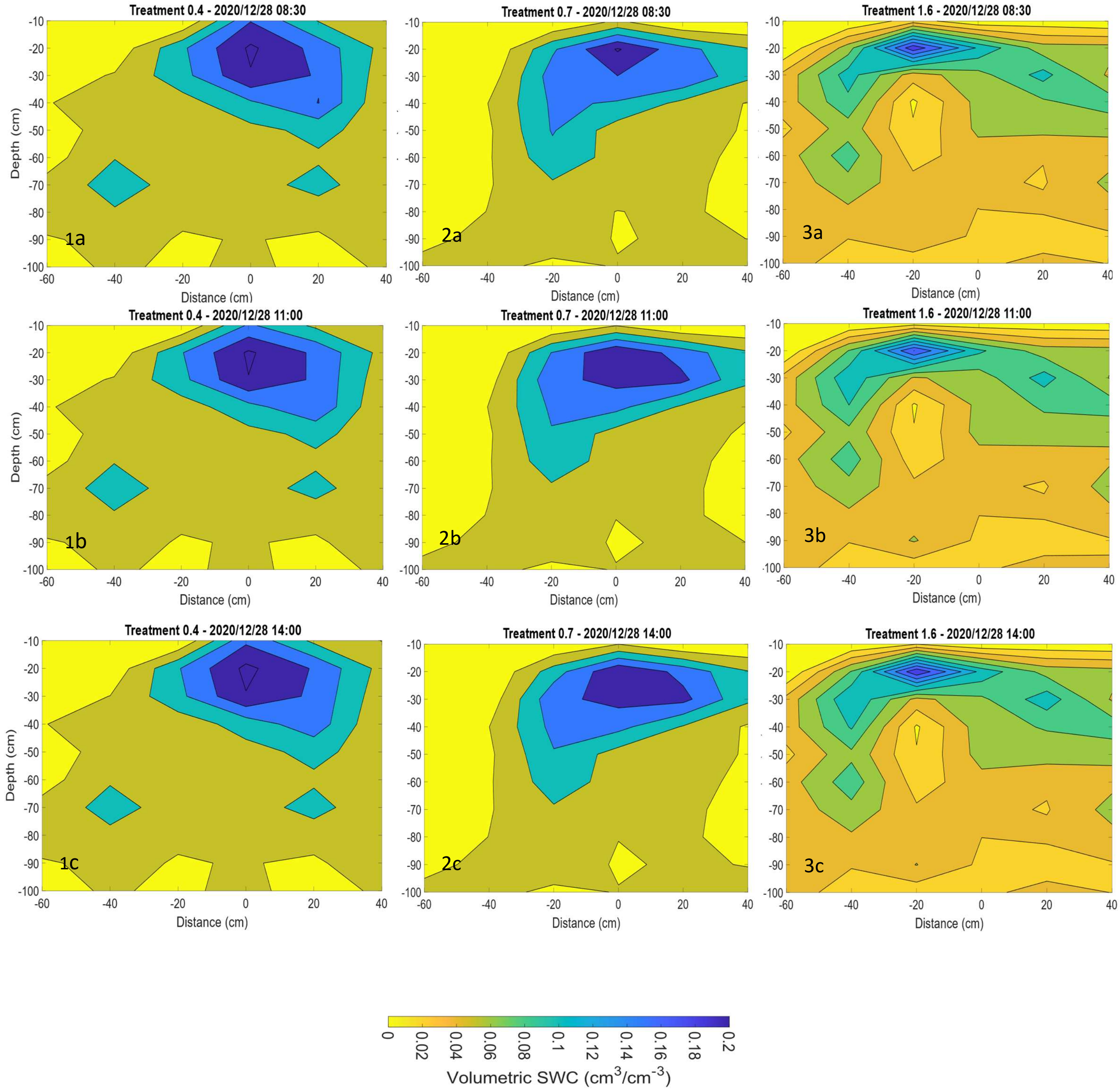

Figure 4.14 a: Spatial distribution of volumetric soil water content across the ridge for continuous drip irrigation with different treatments of drip discharge rate on the 28th of December 2021 at 08:30, 11:00 and 14:00 AM.

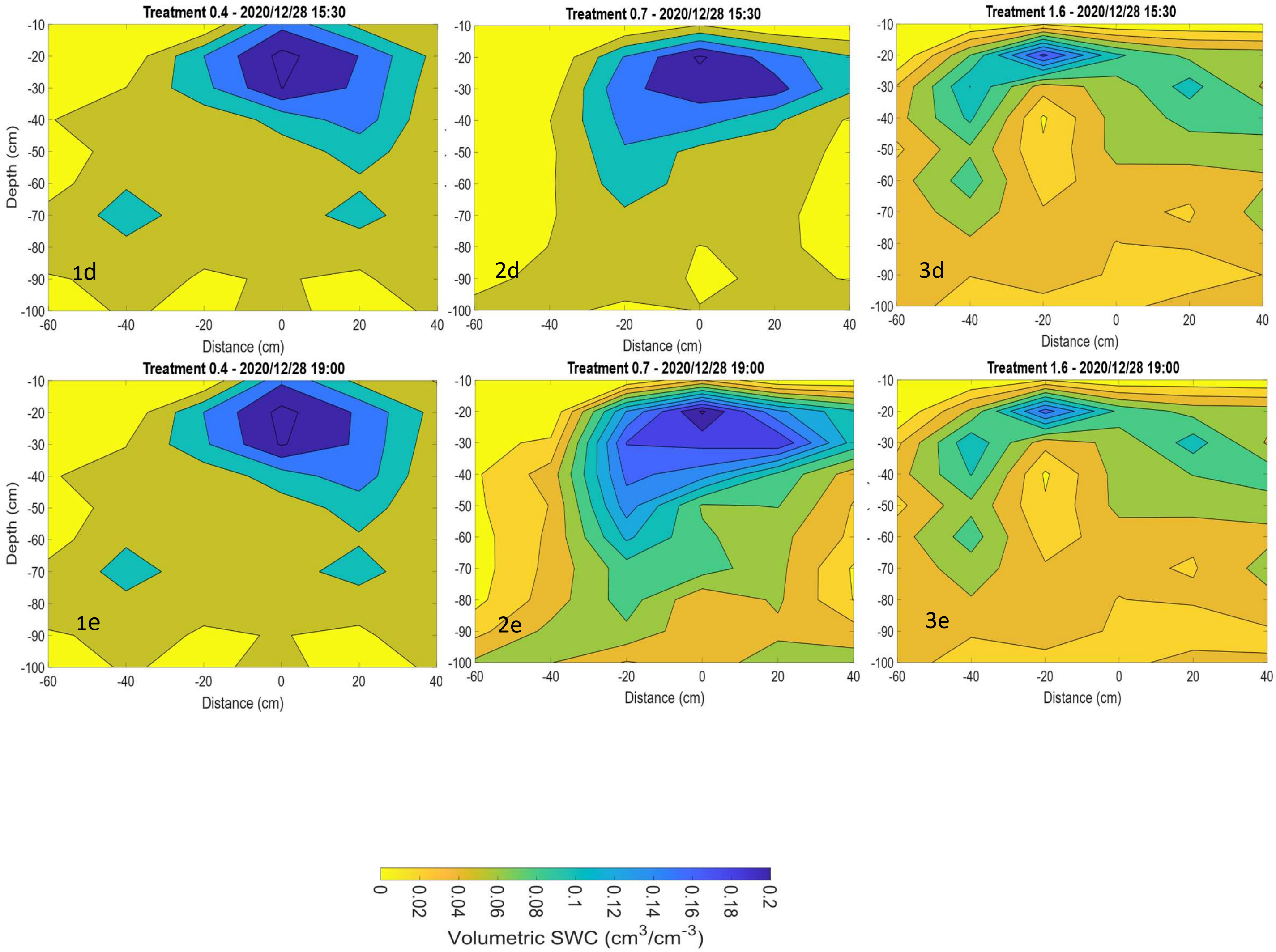

Figure 4.14 b: Spatial distribution of volumetric soil water content across the ridge for continuous drip irrigation with different treatments of drip discharge rate on the 28th of December 2021 at 15:30 and 19:00 PM.

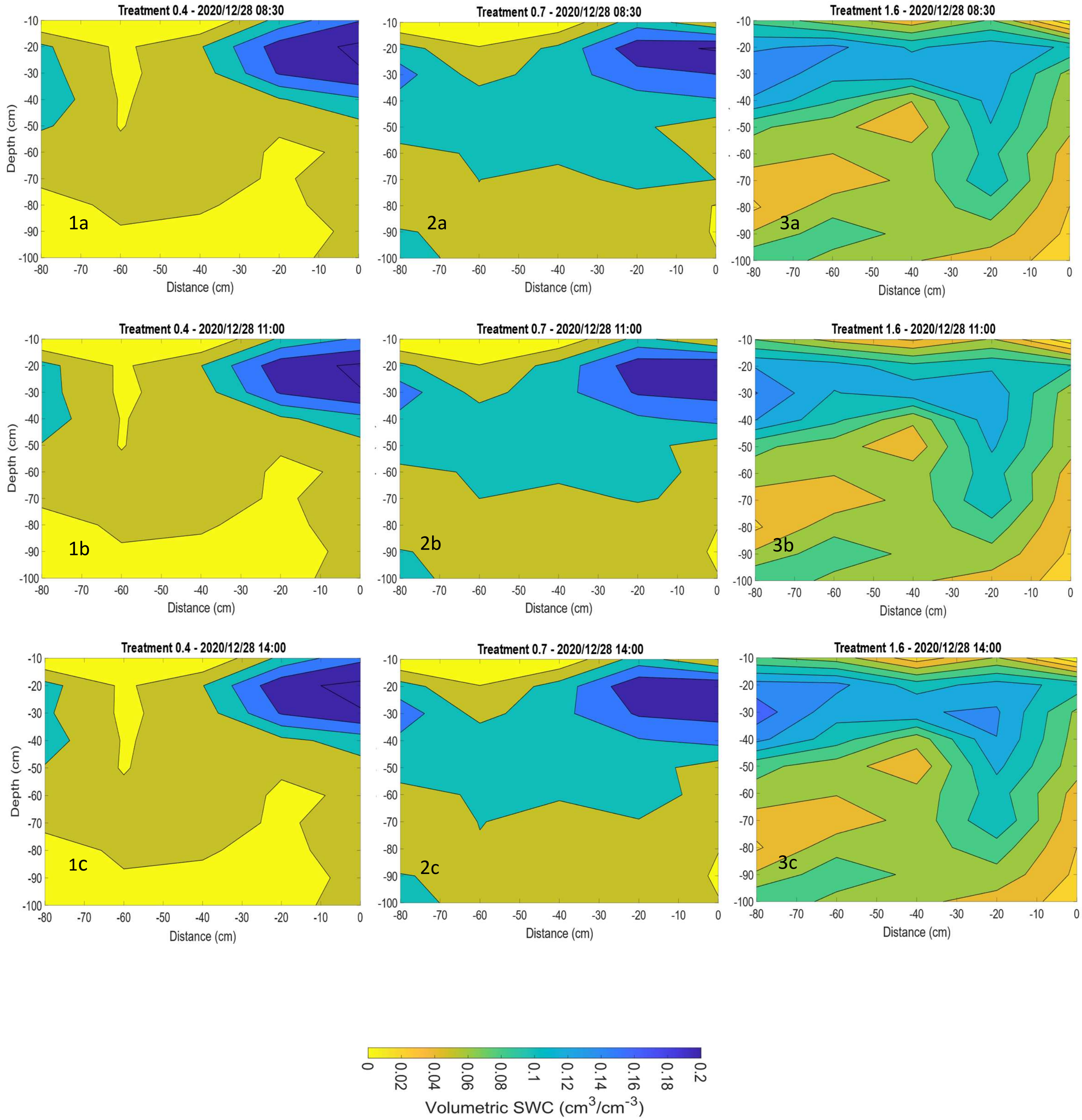

Figure 4.15 a: Spatial distribution of volumetric soil water content parallel with the ridge for continuous drip irrigation with different treatments of drip discharge rate on the 28th of December 2021 at 08:30, 11:00 and 14:00 AM.

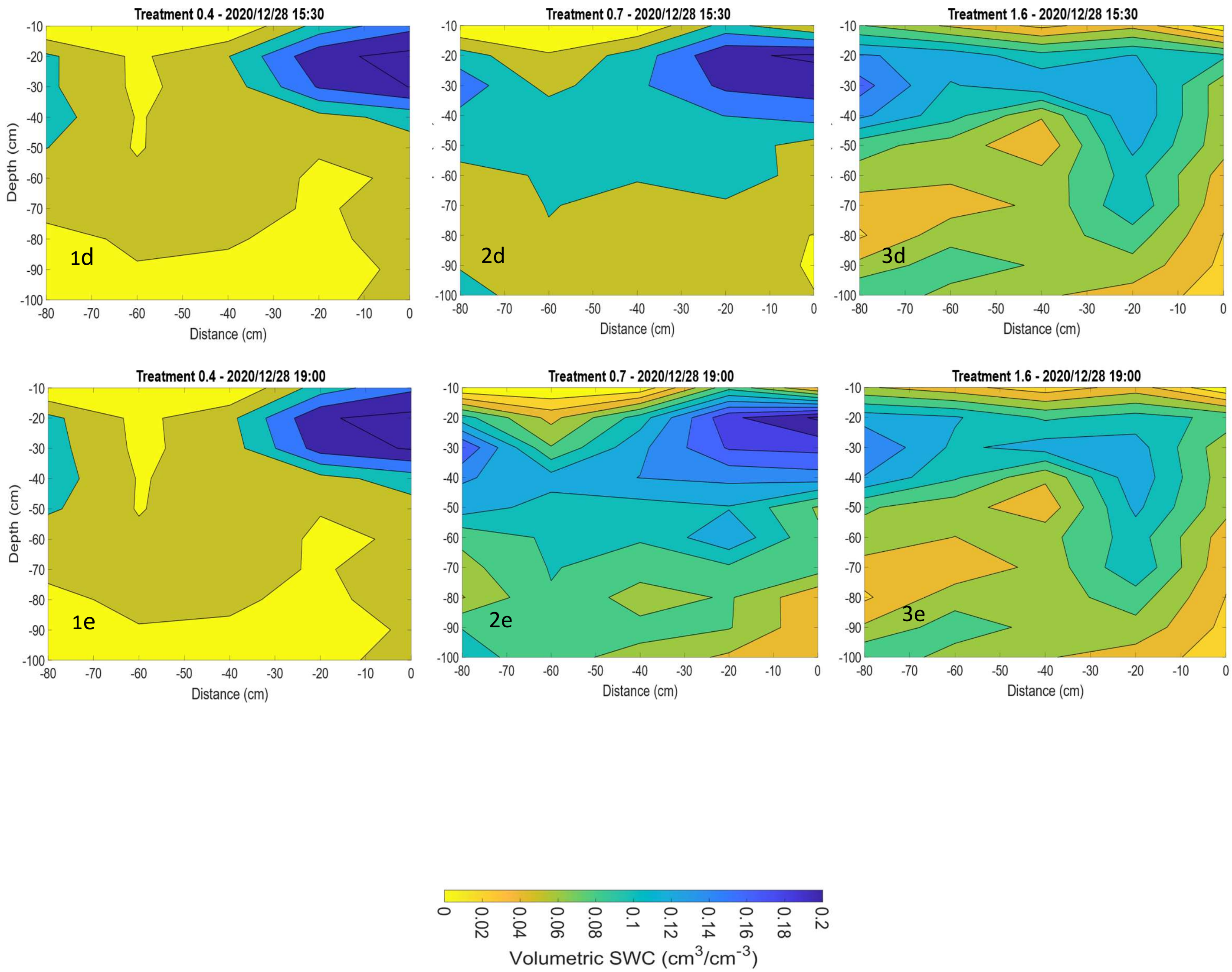

Figure 4.15 b: Spatial distribution of volumetric soil water content parallel with the ridge for continuous drip irrigation with different treatments of drip discharge rate on the 28th of December 2021 at 15:30 and 19:00 PM.

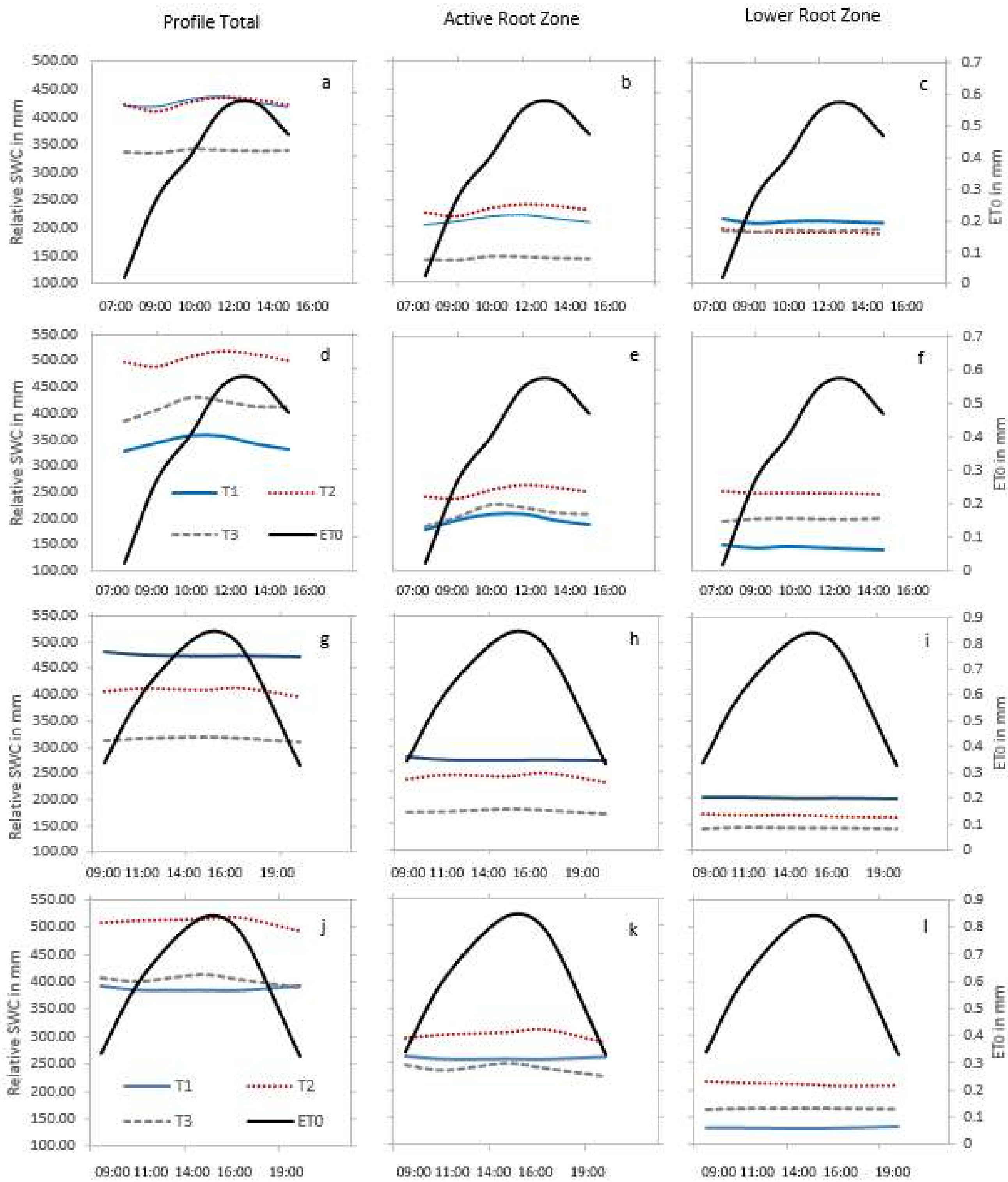

Figure 4.16: Relative SWC fluctuation during the day in relation to Reference evapotranspiration (ETo) rate on the 19th of October (a-f) 2021 and 28th of December 2021 (g-l) for different treatments of drip discharge rate.

Chapter 5: Study of root distribution of 4-year-old 'Nadorcott' mandarin trees ('Carizzo' citrange rootstock) in response to continuous drip irrigation.

5.1 Introduction

There has always been a question as to what effect the duration and frequency of irrigation has on the root system for deep rooted crops (Castle , 1978). Various authors (Glenn, 2000; Marler and Davies, 2019; Michelakis, Vougioucalou and Clapaki, 1993) stated that irrigation method and scheduling directly affects the soil water regime which indirectly affects edaphic factors such as soil strength, aeration and fertility, thus influencing root growth and -distribution. The introduction of drip irrigation and fertilization techniques changed the root system structure dramatically (Spiegel - Roy and Goldschmidt, 1996). Cohen *et al.* (2006) and Assouline (2002) mentioned that irrigation frequency and emitter discharge rate are some of the main factors which determine the soil moisture regime, the resulting root distribution and water uptake patterns.

With the development of low discharge rate drippers, introducing a continuous irrigation approach to citrus cultivation, root observation of young trees are of the essence as the effects of irrigation are likely to be more evident with younger trees or in areas where rainfall is limited and water is supplied by low volume "under-the-tree" systems (Castle, 1978). Citrus root growth generally occurs in two to three flushes annually (Bevington and Castle, 1985). When soil temperature is not limiting, citrus root growth may occur throughout the year and may be controlled by irrigation timing (Bevington and Castle, 1985). Soil temperatures ranging between 13 and 36°C with optimal of 26°C and soil water potential above -0.05 MPa promote root growth when aeration and nutrient availability is adequate (Bevington and Castle, 1985; Bravdo and Proebsting, 1993; Spiegel - Roy and Goldschmidt, 1996). Root growth is known to be vigorous in sandy soils (Castle,1978) with mean elongation rate of 1.6 to 6.6 $mm.day^{-1}$ for 'Carizzo' citrange pioneer roots recorded in a deep sandy soil by Bevington and Castle (1985).

In general, citrus irrigated with drip results in an increased concentration of fibrous roots in the confined volume of irrigated soil under the dripper (Falivene, 2005; Glenn, 2000;

Kadyampakeni *et al.*, 2014) Daily drip is known to limit the root system to a restricted volume of the soil, which has a large capacity to supply water to above ground growth due to continuous provision of optimal soil water potential to a part of the root system and low dependence on soil water movement (Glenn, 2000; Bravdo and Proebsting, 1993). According to Glenn (2000) roots will develop more rapidly in a given environment if other parts of the root system have less access to resources and this portion growing in the wetted region functions as the primary tissue of water and nutrient uptake and hormone production.

Kadyampakeni *et al*. (2014) conducted a study to investigate the effect of intensive fertigation management on root length density and water distribution patterns associated with young Hamlin orange trees on swingle rootstock. In the first year of the study, root samples showed that 64 to 82% of the fibrous roots were concentrated in irrigated zones of both restricted micro sprinkler and drip irrigation with only 18 to 36% concentrated in the non-irrigated zones.

Pijl (2001) investigated the water distribution and resulting root distribution under 1.6 L.h^{-1} drippers, one dripper per tree close to the tree stem. Highest root concentration was in the vicinity of the dripper. In an area of 60 cm vertical depth and 20 cm horizontally which represented 19% of the profile wall area, 83% of the roots were found. This correlated with the extend of the water distribution recorded with EnviroScan capacitance probes (Pijl, 2001).

Under soil water deficit conditions ,the root distribution is modified and roots tend to grow deeper in the soil resulting in an increased root/shoot ratio due to root growth being less reduced than shoot growth (Pérez-Pérez *et al.*, 2008)**.** Root growth tends to decrease or stop in dry regions while continuing in irrigated areas due to reduced carbon partitioning to dry roots (Glenn, 2000).

The relationships between soil properties, drip delivery rate and the resulting water distribution for conventional emitters (>1 L.h^{-1}) are well documented but not so for low and ultra- low delivery rate emitters. Lowering the discharge rate closer to plant uptake rate, allowing continuous low flow irrigation would imply changes in the extent of the wetted soil volume and the gradients of water contents therein. In general, the wetted soil volume can be characterised by a high to low water content gradient from the emitter toward the periphery of the wetted soil volume (Bouksila, Slama and Berndtsson, 2005; Bravdo and Proebsting, 1993). This would imply an inverse for oxygen while roots along this gradient are subject to different soil water potentials. This could imply that no roots are present in the saturated zone under the dripper or formed roots would die back due to interference with the respiration process and ultimately root elongation and division, mineral absorption and hormone synthesis (Bravdo and Proebsting, 1993).

The aim of efficient drip irrigation scheduling is to concurrently replenish water deficit within the effective rootzone while minimizing drainage from it (Khedkar, 2015; Pijl, 2001). Root distribution studies in relation to water distribution under drip irrigation for certain soil conditions will give many insights on management decisions especially for younger citrus trees on aspects such as irrigation duration and patterns as well as placement of soil moisture monitoring equipment to ultimately increase the efficiency of irrigation and fertigation (Marler and Davies, 2019). The objectives of this study was therefore to study root distribution of 4– year-old 'Nadorcott' mandarin trees in response to water distribution patterns under three different treatments of continuous drip irrigation: T1-0.4 $L.h^{-1}$, T2-0.7 $L.h^{-1}$ and T3-1.6$L.h^{-1}$, with the same amount of water and fertilizer applied per treatment.

5.2 Results and Discussion

5.2.1 Root studies October 2019

Root studies performed in October 2019 during spring, served as a baseline study before change in drip irrigation treatments took place and these studies represent root distribution of trees established with 0.7 $L.h^{-1}$ drippers (Figure 5.1). Highest percentage of fine roots (<2 mm) were concentrated in the 20 to 40 cm depth, accounting for 43% of the fine roots. The medium roots (2-5 cm) were concentrated a bit deeper at the 30 to 50 cm depth, accounting for 38% of the medium roots. The roots being concentrated deeper in the profile are suitable for this site as the trees are young on free draining sandy soils that become very hot in the upper 10 cm during the day which is unfavourable for root growth in the topsoil. As the trees become older and shading more of the surface area, root growth is expected to rise closer to the soil surface.

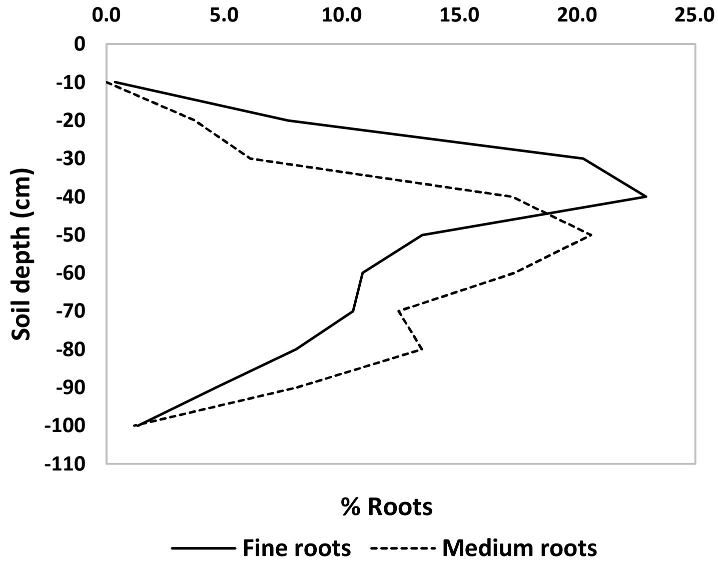

Figure 5.1: Distribution of percentage fine roots (< 2mm) and medium roots (2-5mm) within the soil profile under 0.7 L.h^{-1} drippers in October 2019 before treatments were

5.2.2 Soil conditions

Citrus root growth has been studied by authors such as Bevington and Castle, (1985) Pijl, (2001) Kadyampakeni *et al.* (2014) and (Morgan and Obreza, 2007) and it is known that soil conditions such as soil temperature, soil moisture regime (Bar-Yosef, 1999) pH and concentration of nutrients affect root growth and distribution. Thus, to explain the effect of irrigation treatment, the other factors are taken into consideration as well and discussed.

5.2.2.1 Water distribution

Water distribution patterns parallel with the drip line resulting from short and longer irrigation events on separate days for each treatment are depicted in Figure 5.2. Not a lot of daily variation was observed as discussed in Chapter 3 and the graphs represent where most of the water "resides" in the profile with each irrigation treatment. Soil water content at 14:00 can be seen in Figure 5.2 A to F for separate days during October and December. Water distribution associated with each treatment is discussed in detail in Chapter 3.

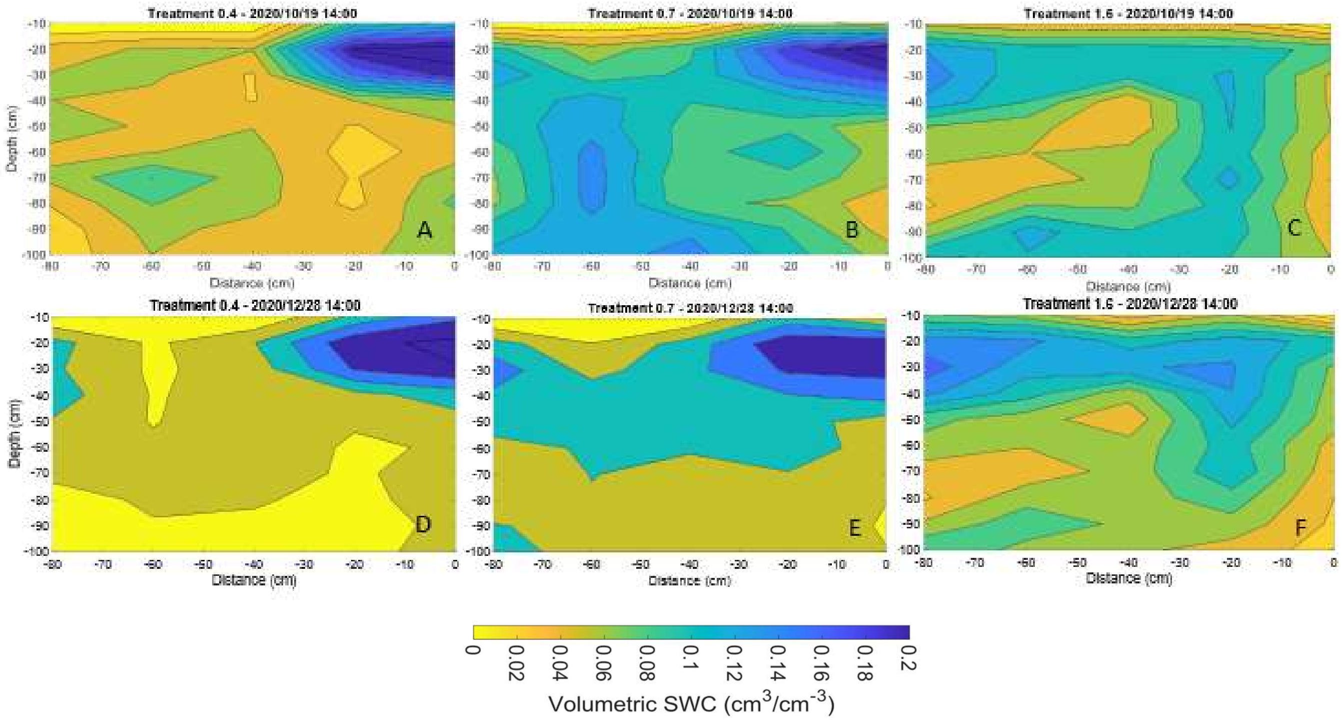

Fig 5.2: Soil water content distribution patterns with each irrigation treatment at 14:00 on separate days during 19 October 2020 and 28 December 2020. A and D represents T1-0.4L.h^{-1}, B and E T2-0.7L.h^{-1} and C and F T3-1.6L.h respectively.

5.2.2.2 Soil Temperature

Soil temperature measured at 15- and 30 cm followed the same trend with each irrigation treatment (Figure 5.3). A general trend of increasing soil temperature was observed from November 2019 until February 2020, with an increase of average soil temperature in November 2019 of 20.9°C to 25.5°C in February 2020. Thereafter soil temperature decreased dramatically towards June 2020 (11.5°C) and decreased more at a slower rate towards August 2020 (11.3°C). Soil temperature recorded from November 2019 until April 2020 was ideal for root growth whereafter root growth was expected to be limited and also cease due to low soil temperature during May 2020 to August 2020. No significant differences in soil temperature was observed among treatments.

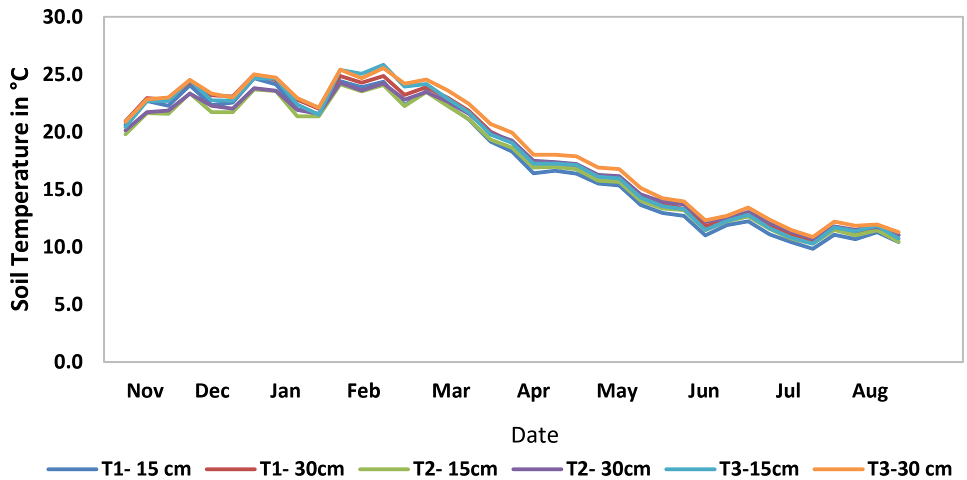

Figure 5.3: Soil Temperature at 15 cm and 30 cm below the soil surface with each irrigation treatment from November 2019 until August 2020.

5.2.2.3 Soil acidity

Soil $pH_{(KCl)}$ measured with depth varied between the three irrigation treatments although a very similar pattern was observed with T1-0.4L.h^{-1} and T2-0.7L.h^{-1} (Figure 5.4). A significant depth and treatment effect were observed, but the depth*treatment interaction was non-significant. A general trend of lower $pH_{(KCl)}$ in the upper 30 cm compared to lower down the profile was observed at the end of the 2019/2020 season with each treatment. This is expected as most applied nutrients through fertigation is concentrated in the upper 30 cm as well as nutrient uptake from fibrous roots, resulting in acidification (Bar-Yosef, 1999; Pijl, 2001). In both T1-0.4L.h^{-1} and T2-0.7L.h^{-1} a higher $pH_{(KCl)}$ is recorded in the 30 to 60 cm depth compared to the upper 30 cm and lower 60 to 90 cm, but this is not observed under T3-1.6L.h^{-1}, that showed similar $pH_{(KCl)}$ values in the 30 to 60 cm and 60 to 90 cm depth. Overall irrigation via the higher discharge rate (T3 -1.6L.h^{-1}) resulted in a soil profile with a relatively higher $pH_{(KCl)}$ than T1-0.4L.h^{-1} and T2-0.7L.h^{-1}. This may be due to less water and fertilizer although the same concentration, applied to a local point due to 50 cm spacing of drippers compared to one meter spacing of T1-0.4L.h^{-1} and T2-0.7L.h^{-1}. Irrigation via 0.7L.h^{-1} (T2) resulted in a significantly lower $pH_{(KCl)}$ in the upper 30 cm than in the 30 to 60 cm depth. No significant difference was recorded with depth for T1-0.4L.h^{-1} and T3-1.6L.h^{-1}.

In the upper 30 cm, higher pH was recorded with T3-1.6L.h^{-1} followed by T1-0.4L.h^{-1} and T2-0.7L.h^{-1} respectively, with significantly lower pH associated with T2-0.7L.h^{-1} than T3-1.6L.h^{-1}. T1-0.4L.h^{-1} Did not differ significantly from the other treatments. At the 30 to 60 depth the same trend was observed, but with very similar pH in T1-0.4L.h^{-1} and T2-0.7L.h^{-1}. Lower down the profile, irrigation via low flow drip irrigation, T1-0.4L.h^{-1} and T2-0.7L.h^{-1}, resulted in a significantly lower pH than T3-1.6L.h^{-1} and may be due to different root structure and more fibrous roots lower down the profile contribution to daily extraction compared to the root structure that formed under daily conventional drip irrigation. Due to spacing differences more water and fertilizer was applied at the position of one dripper with T1-0.4L.h^{-1} and T2-0.7L.h^{-1} compered to T3-1.6L.h^{-1} and may have also largely contributed to this difference.

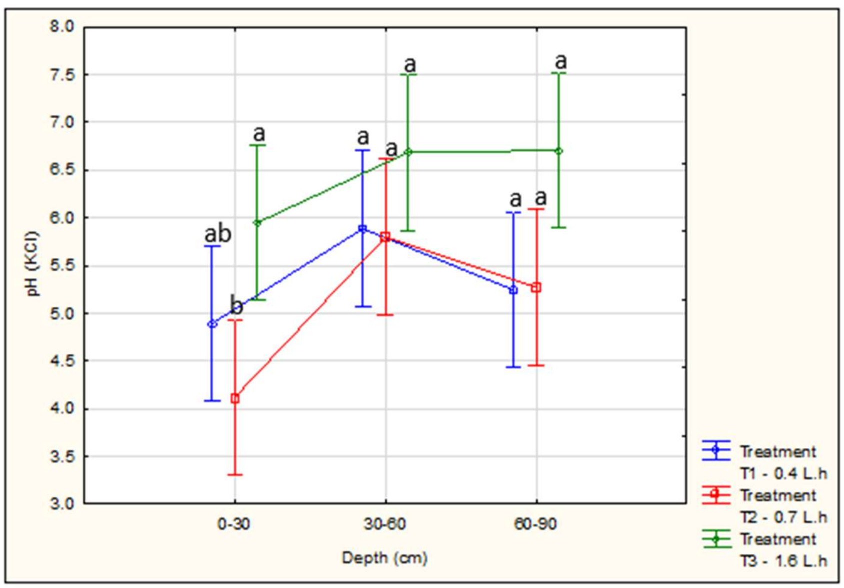

Figure 5.4: Soil pH (KCl) distribution with depth within the soil profile at the end of the season (2019/2020) associated with each irrigation treatment. Treatment means with different letters within a column differ significantly (*p* ≤ 0.005). Vertical bars denote ± SE.

5.2.2.4 Electrical conductivity (EC)

At the end of the season, irrigation via three different discharge rate drippers resulted in increasing EC in the upper 30 cm as the discharge rate decreased (Figure 5.5). This trend was not followed down the profile. At 30 to 60 cm depth very similar EC were recorded for all three treatments ranging from 0.16 to 0.2 mS/cm. Lower down the profile at 60 to 90 cm irrigation via 0.7L.h^{-1} drippers (T2-0.7L.h^{-1}) resulted in higher EC, followed by T1-0.4L.h^{-1} and T3-1.6L.h^{-1} respectively. Significantly lower EC was recorded at this depth under T3-1.6L.h^{-1} than T2-0.7L.h^{-1}. EC at 60 to 90 cm did not differ significantly between T1-0.4L.h^{-1} and T3-1.6L.h^{-1}. Although very low EC was recorded in the soil, a higher EC resulted at the 60 to 90 cm depth with T1-0.4L.h^{-1} and T2-0.7L.h^{-1} than T3-1.6L.h^{-1} and implies that more fertilizer moved beyond the active root zone with the lower discharge rates. Thus, also implying that slightly less fertilizer moved beyond the active root zone with the ultra-low flow drip (T1-0.4L.h^{-1}) compared to the low flow drip treatment (T2-0.7L.h^{-1}).

Each treatment showed a different pattern in EC distribution with depth. Very low discharge rate (T1-0.4L. h^{-1}) resulted in a similar EC in the upper 30 cm than lower in the profile at the 60 to 90 cm depth (ranging from 0.28 to 0.29 mS/cm). A sharp decrease is observed at 30 to 60 cm depth with an EC of 0.16 mS/cm. Irrigation via a slightly higher discharge rate (T2 - 0.7L.h^{-1}) resulted in a more uniform EC distribution in the upper 60 cm (slightly lower in the 30 to 60 cm depth) ranging from 0.2 to 0.22 mS/cm. A sharp increase is observed in the lower profile to an EC of 0.34 mS/cm. The most uniform distribution in EC resulted from the daily conventional irrigation treatment (T3 -1.6L.h^{-1}) with lowest EC in the lower profile (60 - 90 cm) and highest in the middle of the profile (30-60 cm) ranging from 0.13 to 0.17 mS/cm. Overall, soil EC levels for all three treatments were low and did not pose any salinity risk. Low soil EC may be due to daily application of enriched water (fertigation) at lower EC levels.

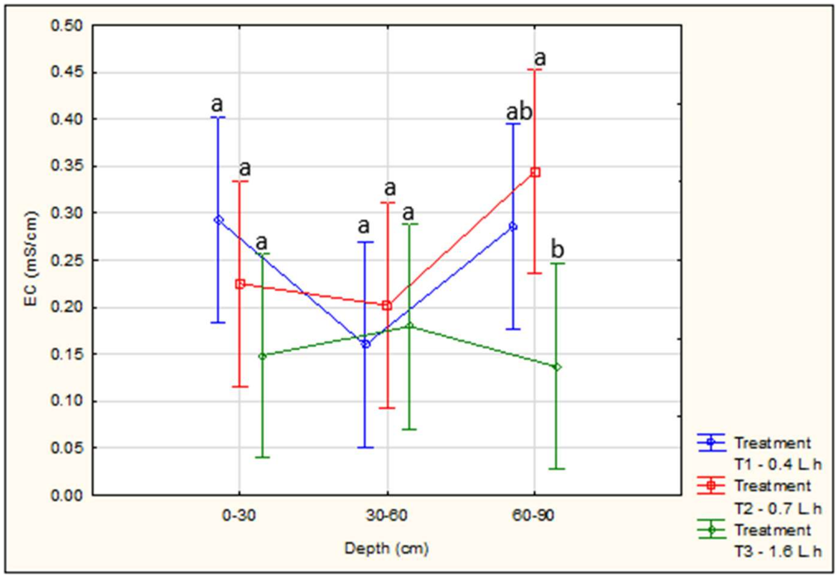

Figure 5.5: Electrical conductivity (EC) in mS/cm with depth in the soil profile at the end of the season (2019/2020) associated with each irrigation treatment. Treatment means with different letters within a column differ significantly (*p* ≤ 0.005). Vertical bars denote ± SE.

5.2.3 Root studies October 2020

From the graphical illustrations (Figures 5.6 to 5.8) of the average root distribution for each treatment, a clear observation can be made of the spatial distribution of roots in the soil profile under each irrigation treatment after one season. All three treatments showed a deep root penetration with roots present up to 90 cm, the depth unto which observations were made. Overall, the root profiles consisted of majority fine roots followed by medium roots and thick roots respectively as expected. Little 'very thick' roots (> 10 mm) were present under all three treatments. Under T2-0.7L.h^{-1}, very little number of roots were present in the top 20 cm of the profile compared to T1-0.4L.h^{-1} and T3-1.6L.h^{-1} that showed very little amount of root in the top 10 cm but an increase in roots observed below 10 cm. Thus, more roots were observed closer to the soil surface under T1-0.4L.h^{-1} and T3-1.6L.h^{-1} compared to T2-0.7L.h^{-1}.

By inspection of the spatial distribution of roots between treatments a difference was observed in 'zones' where higher root densities were present. T1-0.4L.h^{-1} showed more roots concentrated closer to the tree with fewer roots in the middle of the profile. Under T2-0.7L.h^{-1}, a tendency of higher root density was observed in the middle of the profile, between adjacent trees, thus more roots distributed further from the tree. Root distribution associated with T3-1.6L.h^{-1} indicated a strip of high root density across the profile in the 10 to 40 cm depth zone.

By inspection of the graphical presentation a more uniform root distribution with depth is observed under T1-0.4L. h^{-1} compared to T2-0.7L. h^{-1} and T3-1.6L. h^{-1}, that showed zones where more roots were concentrated as mentioned above, with the least uniform root profile associated with T3-1.6L. h^{-1} due to a strip of fine roots in the 10 to 40 cm depth zone.

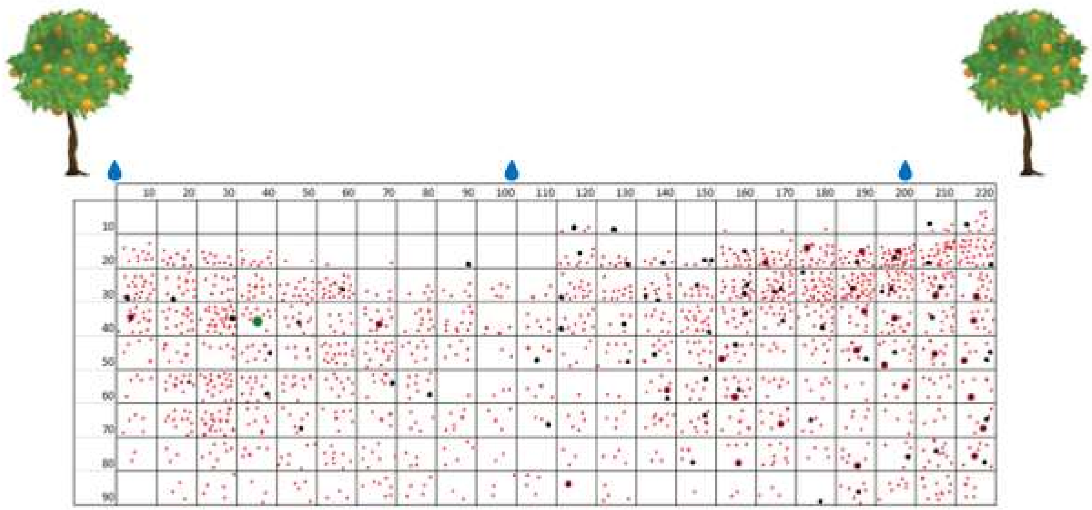

Figure 5.6: A graphical illustration of average spatial root distribution for different classes of roots observed under, T1- 0.4 L.h^{-1} drip discharge rate. Each roots size is represented by a symbol • < 2mm, • 2-5mm, ● 5-10mm, ● > 10mm. Dripper position is represented by the symbol on the graph.

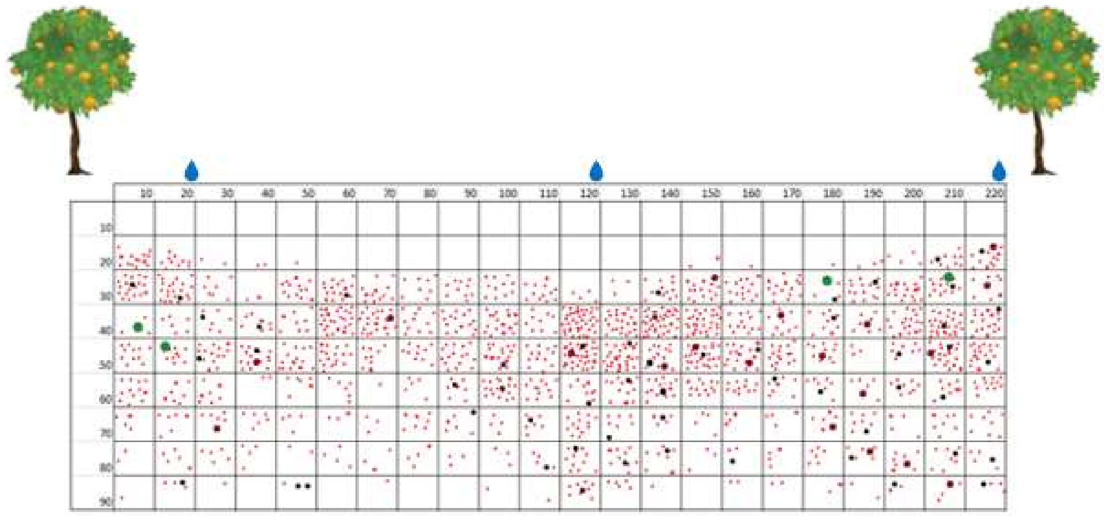

Figure 5.7: **A graphical illustration of average spatial root distribution for different classes of roots observed under, T2- 0.7 L.h^{-1} drip discharge rate. Each roots size is represented by a symbol • < 2mm, • 2-5mm, ● 5-10mm, ● > 10mm. Dripper position is represented by the 💧 symbol on the graph.**

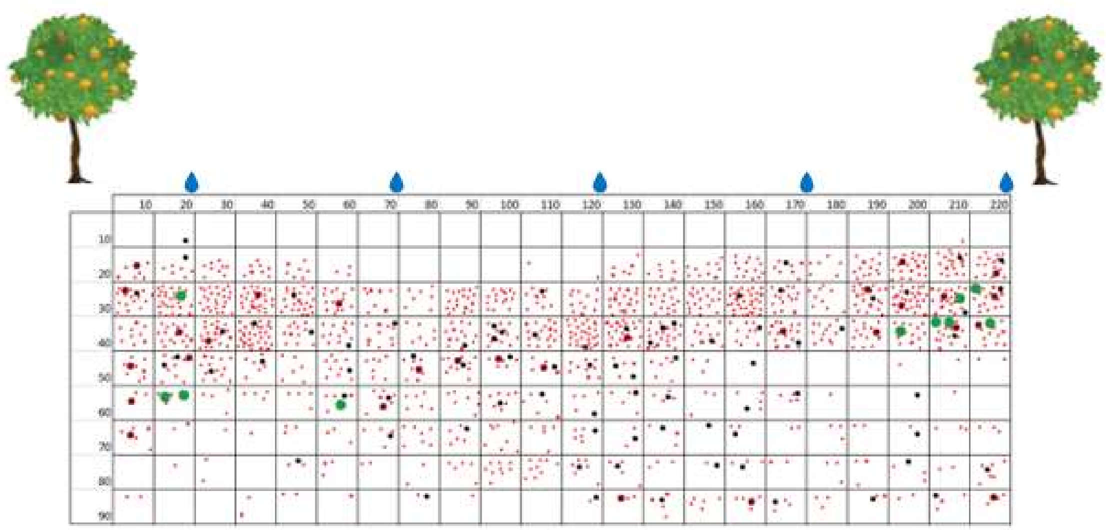

Figure 5.8: **A graphical illustration of average spatial root distribution for different classes of roots observed under, T3- 1.6 L.h^{-1} drip discharge rate. Each roots size is represented by a symbol • < 2mm, • 2-5mm, ● 5-10mm, ● > 10mm. Dripper position is represented by the 💧 symbol on the graph.**

5.2.3.1 Fine roots

Root studies showed that 80% of the fine roots (< 2 mm) were present up the 60 - 70 cm depth under T1-0.4L.h^{-1}, slightly deeper that T2-0.7L.h^{-1} and T3-1.6L.h^{-1} where 80% of the fine roots were observed in the upper 60 cm (Figure 5.9). This observation differs to what some of literature state about citrus fibrous root growth (Morgan and Obreza, 2007) and shows a larger soil volume that contributes to fibrous root distribution, responsible for rapid uptake of water and nutrients (Castle, 1978) but confirms the notion of roots growing deeper in sandy soils and Carrizo citrange root stock showing vigorous growth (Castle, 1978) (Bevington and Castle, 1985; Morgan and Obreza, 2007). Khedkar (2015) mentioned the effective root zone, of which the fibrous roots contribute the most is one to two thirds the depth of the deepest roots, in the case of this study two thirds and more.

In terms of depth with highest percentage of fine roots observed at a specific depth for each treatment, the treatments showed a different pattern of root distribution with depth. Highest percentage of roots were distributed in the 10 to 30 cm depth for T1-0.4L.h^{-1}, 30 to 50 depth for T2-0.7L.h^{-1} and 20 to 40 cm for T3-1.6L.h^{-1}. Percentage roots in these depths were equal to 39.8%, 40.9% and 55.4% for T1-0.4L.h^{-1}, T2-0.7L.h^{-1} and T3-1.6L.h^{-1}. respectively and correspond with zones of highest root density (Table 5.1). The soil layers with highest root density recorded was associated with T3-1.6L.h^{-1} in the 20 -30 cm layer, 1786 roots/m² followed by T2-0.7L.h^{-1} in the 30 to 40 cm layer (1595 roots/m²) and T1-0.4L.h^{-1} in the 20 -30 cm layer (1439 roots/m²) respectively. Overall, this shows the effect of frequent drip irrigation, bringing fine root distribution and high root density close to the soil surface.

For all three treatments fine roots where present up to 90 cm, the maximum depth of the root studies, but at very low percentages, 4.6, 2.8 and 3.4% for T1-0.4L.h^{-1}, T2-0.7L.h^{-1} and T3-1.6L.h^{-1} respectively. In the 0 to 10 cm depth no fine roots were observed under T2-0.7L.h^{-1} with neglectable fine roots under T3-1.6L.h^{-1} (0.05%). Fine roots amounted to 2.2% in the 0- 10 cm depth under T1-0.4L.h^{-1}. In the 10 to 20 cm depth zone, a significant higher percentage of roots were observed with T1-0.4L.h^{-1} (17.84%) than T2-0.7L.h^{-1} (4.02%), but no statistically significant difference in relation to T3-1.6L.h^{-1} (11.73%). Root densities at this depth were equal to 965, 271 and 719 roots/m² respectively.

Daily conventional drip (T3-1.6L.h^{-1}) resulted in significantly higher % of roots in the 20 to 30 cm depth zone compared to T2-0.7L.h^{-1}, with no statistically significant difference in relation to T1-0.4L.h^{-1}. Root percentages in this depth zone accounted for 21.99, 16.49 and 29.51% of the total fine roots and root densities of 1439, 1118 and 1786 roots/m^2 for T1-0.4L.h^{-1}, T2-0.7L.h^{-1} and T3-1.6L.h^{-1} respectively. Thus, higher fine root density was observed closer to the soil surface by applying water at a lower discharge rate over a longer period (T1-0.4L.h^{-1}) compared to T2-0.7L.h^{-1} and T3-1.6L.h^{-1}. This agrees with the notion of root proliferation in areas with increased water and nutrient availability (Falivene, 2005). T1-0.4L.h^{-1} resulted in a smaller wetted volume parallel with the drip line compared to T2-0.7L.h^{-1} and may have resulted in increased root density and fine root distribution closer to the surface where a higher percentage of water was available compared to the rest of the soil profile for this treatment. T3-1.6L.h^{-1} also showed a higher root density, although lower SWC in this area compared to T2-0.7L.h^{-1} but higher SWC proportional to the rest of the soil profile for this treatment. This agrees with findings from Coleman (2007) and Michelakis, Vougioucalou and Clapaki (1993) that roots adapt proportionally to grow and increase in density in areas with increased resource availability.

Comparing the % fine root distribution with depth with the graphical illustration of root distribution (Figures 5.6 to 5.8) a good correlation can be drawn between the graphs, showing fine roots close to the soil surface under T1-0.4L.h^{-1}, more fine roots present deeper in the profile under T2-0.7L.h^{-1} and a high concentration of fine roots in 20 to 40 cm depth zone associated with T3-1.6L.h^{-1}. This fibrous root distribution corresponds with the water distribution under each treatment: T1-0.4L.h^{-1} resulted in less overlap of wetted soil volumes and closer to the emitter thus fine roots concentrated closer to the tree and closer to the soil surface as well. T2-0.7L.h^{-1} showed more overlap of the wetted soil volumes deeper in the soil profile between adjacent drippers, promoting roots to grow away from the dripper resulting in more roots in the middle of the profile between the trees. T3-1.6L.h^{-1} resulted in a wetted strip and a shallow irrigation depth as seen in Chapter 3 which allowed favourable conditions for a concentrated band of roots to form in 20 to 40 cm depth zone. Overall T2-0.7L.h^{-1} showed very similar fine root distribution compared to roots studies done in October 2019 with the onset of the trial.

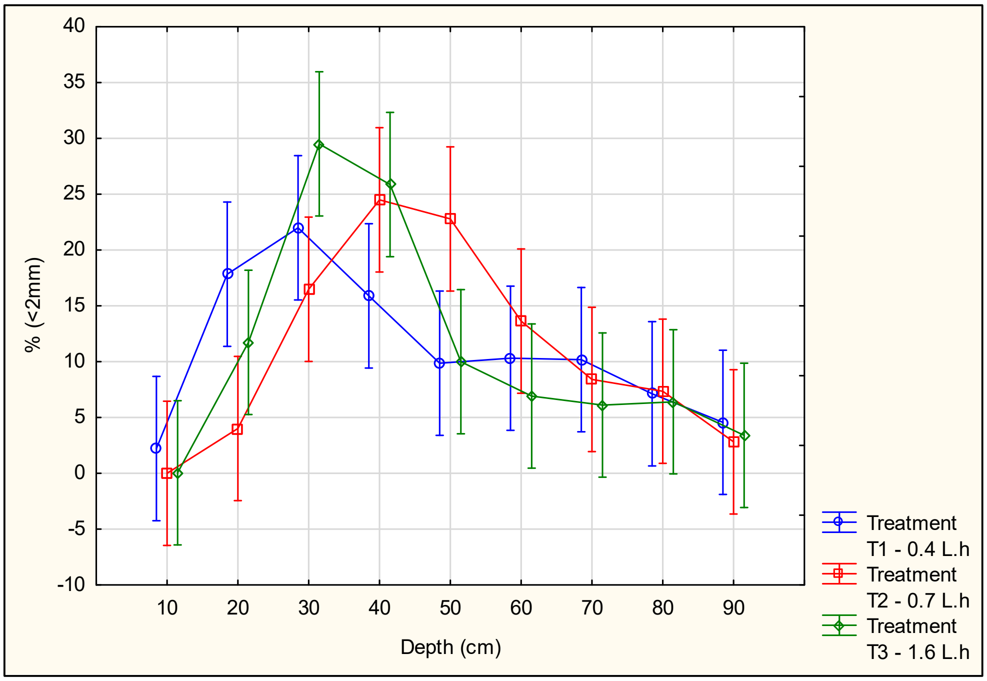

Figure 5.9: Percentage fine roots (diameter < 2 mm) in particular soil layers for different treatments of drip discharge rate: T1- 0.4 L.h^{-1}, T2- 0.7 L.h^{-1} and T3-1.6L.h^{-1}. Vertical bars denote ± SE.

Table 5.1. Average number of fibrous roots/m² (diameter < 2 mm) in particular soil layers for different treatments of drip discharge rate: T1- 0.4 L.h^{-1}, T2- 0.7 L.h^{-1} and T3-1.6L.h^{-1}.

Depth cm	T1 -0.4 L.h^{-1}	T2 -0.7 L.h^{-1}	T3 -1.6 L.h^{-1}
0 - 10	83.33	0	3.03
10 - 20	965.15	271.21	719.7
20 - 30	1439.4	1118.18	1786.36
30 - 40	1101.52	1595.45	1509.09
40 - 50	707.58	1466.67	540.9
50 - 60	660.61	853.03	351.52
60 -70	619.7	537.88	321.21
70 - 80	495.45	474.24	321.21
80 - 90	343.94	175.76	180.3

5.2.3.2 Medium roots

Medium root distribution with depth varied with each treatment. Observing Figure 5.10, a sharp increase in medium roots were observed under T2-0.7L. h^{-1} and T3-1.6L. h^{-1} in the 40 to 50 cm and 30 to 40 cm depth respectively accounting for 22.18 and 33.71% of the total medium roots. Root densities in these depth zones equalled to 28.79 and 72.73 roots/m² for T2-0.7L.h^{-1} and T3-1.6L.h^{-1} respectively (Table 5.2). Irrigation via 1.6L.h^{-1} drippers (T3-L.h^{-1}) resulted in significantly higher root density ($p < 0.05$) in the 30 to 40 cm layer than T2-0.7L.h^{-1} but not T1-0.4L.h^{-1}, with root densities of 72.73, 16.67 and 28.79 roots/m² respectively. T1-0.4L.h^{-1} resulted in a more uniform distribution of medium roots in terms of percentage roots per depth as illustrated in Figure 4.10 with highest density in the 20 to 30 cm depth zone (54.55 roots/m²). Eighty percent of the medium roots were present in the upper 70 cm for T1-0.4L.h^{-1} and upper 80 cm for T2-0.7L.h^{-1} and T3-1.6L.h^{-1}. Medium roots were present up to 90 cm for all three treatments, the depth of observation.

In the upper 30 cm, 32.27, 14.06 and 15.14% of the medium roots were observed with T1-0.4L. h^{-1}, T2-0.7L. h^{-1} and T3-1.6L. h^{-1} respectively, whereafter an increase in roots % occurred in the middle of the profile for T2-0.7L. h^{-1} and T3-1.6L. h^{-1}. Thus, applying water at a very low rate resulted in roots growing closer to the soil surface (Figure 5.10), thus following the same trend as the fine roots. In the top 10 cm of the profile no medium roots were observed under T2-0.7L. h^{-1}, 0.65% under T3-1.6L. h^{-1} and highest percentage associated with T1-0.4L. h^{-1} (2.84%). Comparing the percentage medium roots per depth with the graphical illustration of the average roots distribution in the profile (Figures 5.6 to 5.8) it is clear that the medium roots contribute to the observation made of more roots growing closer to the soil surface under T1-0.4L.h^{-1}, in a concentrated strip under T3-1.6L.h^{-1} and at deeper soil layers under T2-0.7L.h^{-1}, corresponding with the water distribution patterns as explained previously.

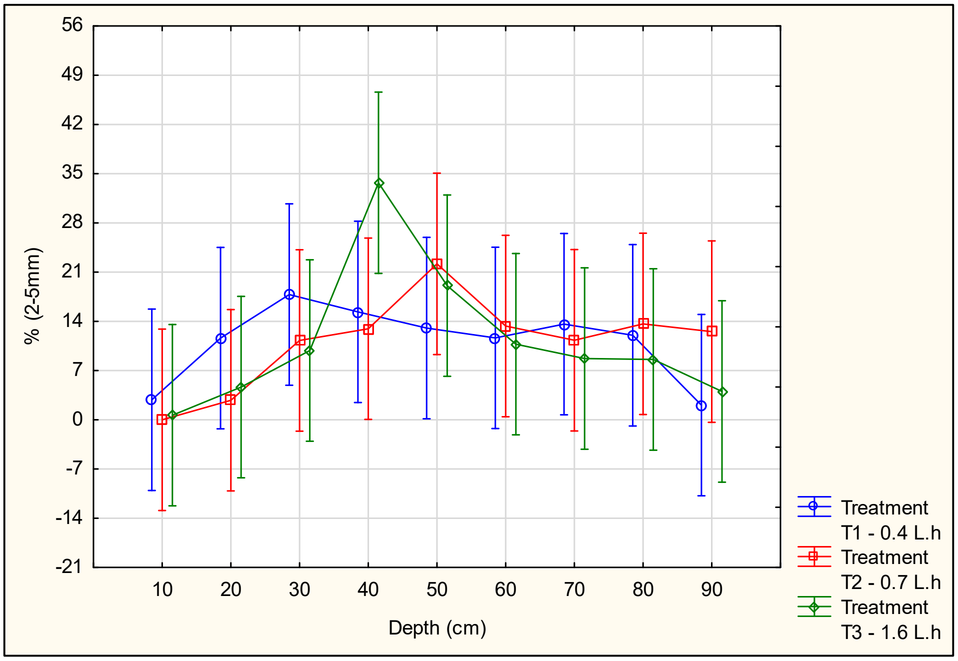

Figure 5.10: Percentage medium roots (diameter 2-5 mm) in particular soil layers for different treatments of drip discharge rate: T1- 0.4 L.h^{-1}, T2- 0.7 L.h^{-1} and T3-1.6L.h^{-1}. Vertical bars denote ± SE.

Table 5.2. Average number of medium roots/m² (diameter 2-5 mm) in particular soil layers for different treatments of drip discharge rate: T1- 0.4 L.h^{-1}, T2- 0.7 L.h^{-1} and T3-1.6L.h^{-1}.

Depth cm	T1 -0.4 L.h^{-1}	T2 -0.7 L.h^{-1}	T3 -1.6 L.h^{-1}
0 – 10	10.60	0	1.52
10 - 20	40.91	3.03	10.61
20 - 30	54.55	15.15	21.21
30 - 40	28.79	16.67	72.73
40 - 50	21.21	28.79	42.42
50 - 60	13.64	18.18	24.24
60 -70	12.12	15.15	19.7
70 - 80	10.61	18.18	19.7
80 - 90	3.03	16.67	9.09

5.2.3.3 Thick roots

Overall a very low number of thick roots were observed under all three treatments, with highest number of roots associated with T1-0.4L.h^{-1} followed by T3-1.6L.h^{-1} and T2-0.7L.h^{-1} respectively (Figure 5.11). Under T1-0.4L.h^{-1} most of the thick roots were present closer to the soil surface with 74.9% in the upper 40 cm, while 66.7% and only 26.4% in T3-1.6L.h^{-1} and T2-0.7L.h^{-1} respectively. T3-1.6L.h^{-1} and T2-0.7L.h^{-1} showed a rapid increase in thick root % lower down the profile in the 30 to 40 cm and 40 to 50 cm depth respectively. An increase in thick roots were also observed lower down the soil profile with T2-0.7L.h^{-1} with 16.7% of thick roots in the 70-80 cm depth. No thick roots were observed in the upper 10 cm in any of the treatments. The density of thick roots was very low in all three treatments as expected with highest density recorded under T3-1.6L.h^{-1} in the 30 to 40 m depth (18.18 roots/m²) followed by T1-0.4L.h^{-1} also in the 30 to 40 cm depth (12.12 roots/m²) and T2-0.7L.h^{-1} in the 40 to 50 cm depth (10.61 roots/m²). At the 30 to 40 cm T3-1.6L.h^{-1} showed a significantly higher root density than T2-0.7L.h^{-1} but not T1-0.4L.h^{-1}. T1-0.4L.h^{-1} and T2-0.7L.h^{-1} did not differ significantly.

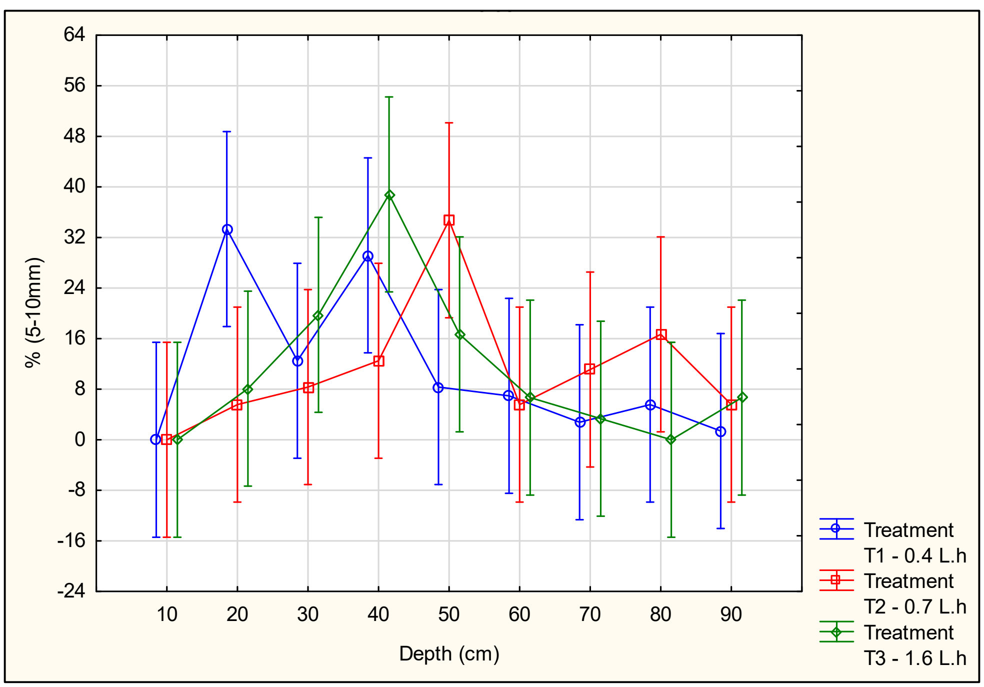

Figure 5.11: Percentage thick roots (diameter 5-10 mm) in particular soil layers for different treatments of drip discharge rate: T1- 0.4 L.h^{-1}, T2- 0.7 L.h^{-1} and T3-1.6L.h^{-1}. Vertical bars denote ± SE.

Table 5.3. Average number of thick roots/m² (diameter 5–10 mm) in particular soil layers for different treatments of drip discharge rate: T1- 0.4 $L.h^{-1}$, T2- 0.7 $L.h^{-1}$ and T3-1.6$L.h^{-1}$.

Depth cm	*T1 -0.4 $L.h^{-1}$*	*T2 -0.7 $L.h^{-1}$*	*T3 -1.6 $L.h^{-1}$*
0 – 10	*0*	*0*	*0*
10 – 20	*7.58*	*1.52*	*4.55*
20 – 30	*4.55*	*3.03*	*12.12*
30 – 40	*12.12*	*4.55*	*18.18*
40 – 50	*9.09*	*10.61*	*12.12*
50 – 60	*7.58*	*1.52*	*3.03*
60 -70	*3.03*	*3.03*	*1.52*
70 - 80	*6.06*	*5.55*	*0*
80 - 90	*1.52*	*1.52*	*4.55*

5.2.3.5 Roots per profile zone

Due to differences observed in the spatial root distribution in the profile as illustrated in Figures 5.6 to 5.8, the profile between trees were divided into three zones. This is illustrated in Figure 5.12, to observe trends and any statistical difference in the spatial growth pattern of roots under each treatment. This is only discussed for the fine roots (< 2 mm). Zone A1 represents the first section 80 cm away from the first tree, zone B the middle 60 cm of the profile wall and A2 the last 80 cm on the right side of the profile wall, left to the adjacent tree.

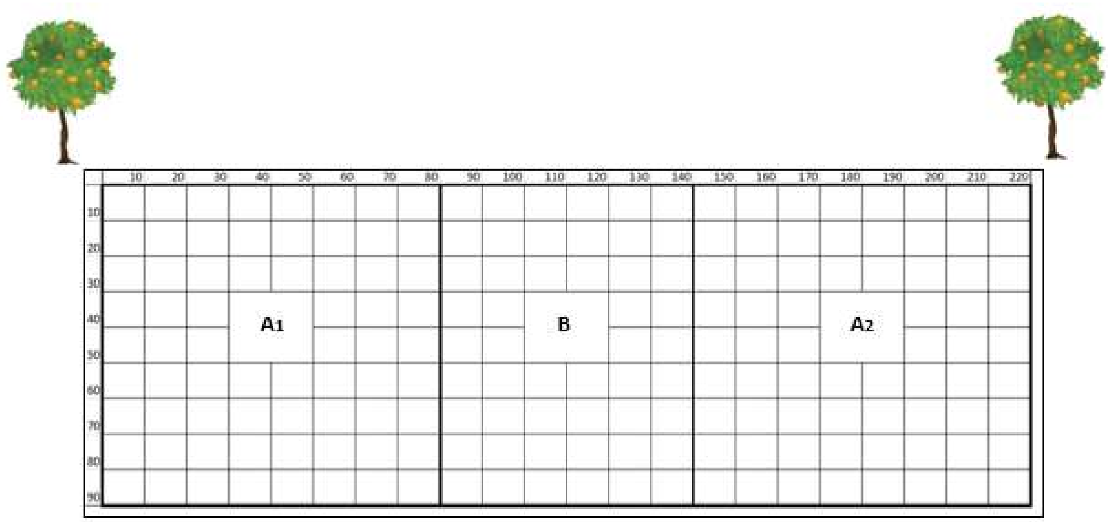

Figure 5.12: Illustration of root zones identified on the profile wall to interpret root distribution across the profile.

Although no statistical significance difference in the density per root zone followed one season of treatments, a general trend with each treatment was observed (Figure 5.13). Applying water at $0.4L.h^{-1}$ (T1) resulted in higher root density in zones A1 and A2 compared to zone B, showing a sharp decrease in root density from 742.6 and 904.2 to 418.5 roots/m² in zone A1 and A2 to B, respectively. Thus, roots are growing closer to the trees and not spreading across the profile as observed with T2-$0.7L.h^{-1}$ and T3-$1.6L.h^{-1}$.

An opposite trend was observed in T2-$0.7L.h^{-1}$ and T3-$1.6L.h^{-1}$ with higher root densities in zone B compared to A1 and A2 and a more pronounced effect associated with T2-$0.7L.h^{-1}$. Root densities in zones A1, A2 and B amounted to 597.7, 745.8 and 853.7 roots/m² respectively for T2-$0.7L.h^{-1}$, indicating roots distributing across the profile. Although this same effect was observed in T3-$1.6L.h^{-1}$, the effect was not so pronounced and a more uniform distribution in root density is evident across zone A1, A2 and B with roots densities of 615.3, 625.5 and 681.5 roots/m² respectively. This corresponds with the strip of roots associated with T3-$1.6L.h^{-1}$ (Figure 5.8) as discussed and a phenomenon associated with frequent shallow irrigation and strip wetting via drip irrigation (Pijl, 2001; Schoeman, 2002). In zone B, the highest root density was recorded with T2-$0.7L.h^{-1}$ followed by T3-$1.6L.h^{-1}$ and T1-$0.4L.h^{-1}$ respectively.

Applying a nutrient solution daily in this study via low discharge rates did not necessarily result in a constricted root zone and well distributed root zone was observed with each treatment. However, T1-$0.4L.h^{-1}$ did result in roots concentrating in zones closer to the tree.

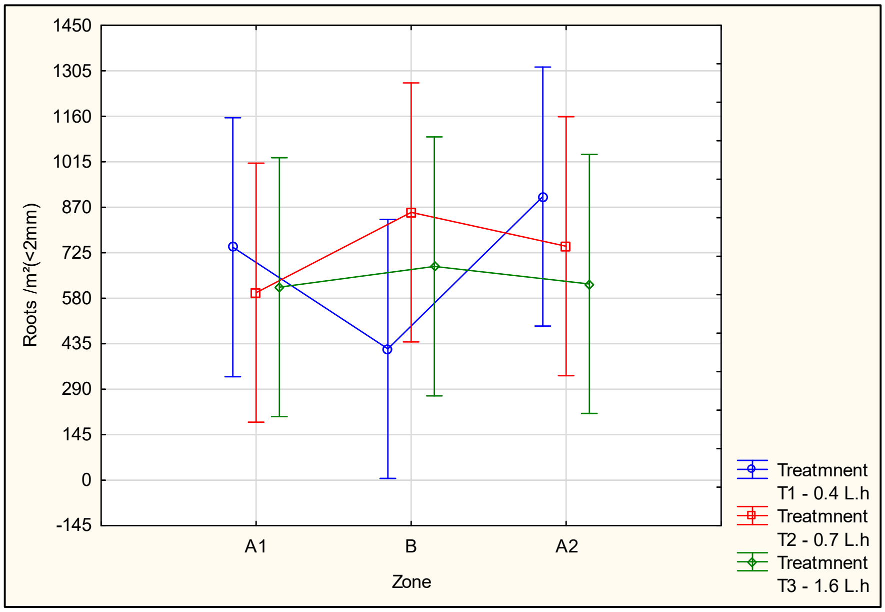

Figure 5.13: Root density (root/m²) distribution in root zones identified on the profile wall as per illustration in Figure 5.12. Vertical bars denote ± SE.

5.3 Conclusion

The results emphasize the importance of irrgation scheduling. Even though the same volume of water was applied, the manner in which it was applied had an effect on root distribution. Irrigation via three different drip discharge rates, ultra-low (T1-0.4L.h^{-1}), low (T2-0.7L.h^{-1}) and daily conventional (T3-1.6L.h^{-1}) resulted in different root distribution patterns represented mainly by the fine and medium root distribution. The observations agree with findings from Kadyampakeni *et al.* (2014) that the finer roots can adapt very fast and would convey where favourable conditions prevailed for root growth under certain environmental conditions (Michelakis, Vougioucalou and Clapaki, 1993). In this case the root zone environment was influenced by different irrigation treatments.

More overlap of adjacent wetted soil volumes with T2-0.7L.h^{-1} may have caused more roots to grow and proliferate deeper down the soil profile and further away from the tree, promoting roots to spread. Although applying the same volume of water over the surface area of the trial site with T3-1.6L.h^{-1} compared to T1-0.4L.h^{-1} and T2-0.7L.h^{-1}, the water application at the local point of delivery (dripper) was less with T3-1.6L.h^{-1} due to narrower spacing of drippers (50 cm). This resulted more in a wetted strip and shallower daily irrigation depth causing roots to grow and proliferate in the 20 to 40 cm depth resulting more in a dense root strip across the profile and higher recorded root density. Ultra-low flow drip (T1-0.4L.h^{-1}) encouraged roots to grow closer to the tree allowing less spreading across the profile with roots developing closer to the soil surface. Highest fine root density was recorded in T3-1.6L.h^{-1} in the 20 -30 cm layer, followed by T2-0.7L.h^{-1} in the 30 to 40 cm layer and T1-0.4L.h^{-1} in the 20 -30 cm respectively.

A concern of daily low discharge irrigation is the risk of water stress effects in the case of power block outs (B Bravdo and Proebsting, 1993), but overall ultra-low, low flow and daily conventional drip irrigation allowed for well-developed root systems beyond the drip zones capable of water exchange between roots as mentioned by Bravdo and Proebsting (1993) to sustain tree and crop growth.

Chapter 6: Fruit growth, yield, and juice characteristics of 'Nadorcott' mandarin under continuous drip irrigation on a sandy soil

6.1 Introduction

Water has a central role of a major metabolic agent in the life of plants (Hillel 1998). The evergreen citrus is a high-water demanding crop with seasonal water requirements varying with climatic demand and phenology (Mostert, 1999; Hoffman, 2006; Shirgure and Srivastava, 2014; Vahrmeijer and Taylor, 2018). Studies on deficit irrigation have shown that citrus clearly responds to irrigation strategy and water availability and that crop response is influenced by timing of water stress rather than accumulated stress over time (Tejero *et al.*, 2011). The response to water stress is mainly reflected in yield and fruit quality due to sensitivity during the phenological stages of flowering and fruit growth stages (García-Tejero *et al.*, 2010; Shirgure and Srivastava, 2014). Mostert (1999) found that water stress during the stage of cell division has an irreversible effect on fruit quality. Hoffman (2006) concluded that the greatest detrimental effect on fruit size and yield was due to water stress in the rapid fruit development stage. When water savings is up to 1000 m³/ ha, effects may be particularly severe (Tejero *et al.*, 2011; García-Tejero *et al.*, 2010).

In recent years the plantings of late maturing mandarins in South Africa increased significantly by 21% in the total area of planted mandarins from 2014 to 2015, more than any other cultivar group (Cronje and Stander, 2016). With this expansion, the use of drip irrigation and fertigation also increased. Method of water application directly influences soil water potential, altering root growth and distribution which in turn influence plant growth (Chartzoulakis, Michelakis and Stefanoudaki, 1999). Different crop responses to drip compared to more traditional irrigation methods are expected due to different water and nutrient distribution in one dimensional and axisymmetric flow regimes as well as increased uniformity of water and nutrient application under drip (Bar-Yosef, 1999). With the development of lower discharge rate emitters certain irrigation applications are allowed aiming to maintain more optimal growing conditions in term of water and nutrient availability. Irrigation approaches such as pulsing, OHS (Falivene, 2005) daily daylight irrigation (Schoeman, 2002) made possible through drip irrigation systems allowing sensitive crop management became another tool to regulate tree development and growth to increase fruit quality and yield (Schoeman, 2002; Glenn, 2000). These application methods aim to create a root environment where root growth relies less on the soil but more on the nutrient medium (Schoeman, 2002; Falivene, 2005; Schumann, Syvertsen and Morgan, 2009). Meagre results are available on the response in citrus crop to different dripper delivery rate irrigation treatments, but more so on the response to soil water status, extraction levels of available plant water and different fractions of reference evapotranspiration applications.

Promising results were found in South Africa showing increased yield of Clementine and Valencia oranges of 25% and 19% respectively under an OHS system compared to micro-irrigation with broadcast fertilizer application (Srivastava, 2015). Trees irrigated with 140% ET yielded 43% more compared to 50, 80 and 110% which did not differ significantly from each other in an drip irrigation (4 $L.h^{-1}$ discharge) trial on five-year old Clementine trees (Castel, 1994). Water extraction level of 20% plant available water resulted in average higher yield, fruit weight, total soluble solids (TSS) and juice % compared to 10 , 30 and 40% extraction levels under drip irrigation (Shirgure, Srivastava and Singh, 2001). Irrigation scheduling at SWP levels of -0.01 MPa (field capacity) and -0.05 MPa via drip indicated no significant difference in yield, fruit number and -weight, juice, TSS or acidity % of ‘Bonanza’ orange trees (Chartzoulakis, Michelakis and Stefanoudaki, 1999). Significantly lower yield and higher TSS % were observed at -1.5 MPa SWP based scheduling and trends of lower juice % and fruit weight and higher acidity. Higher yields of drip irrigated Nagpur mandarins were recorded in a mulch experiment ascribed to higher conserved soil moisture status at 15 and 30 cm depth (Shirgure *et al.*, 2003). Highest juice % (49.86), TSS (10.4°B) and fruit weight were associated with treatments that maintained highest soil moisture status at the 15 and 30 cm depth, although differences in TSS were not significant.

Irrigating with ultra-low drippers has continuous irrigation as a further outcome, addressing many problems faced in irrigation management of citrus orchards in sandy soils. Limited information is available on the response in citrus growth parameters to low discharge drip and soil moisture regimes resulting from continuous drip irrigation. The objectives of this study were therefore to determine the response that change in soil water dynamics resulting from three application rates have on tree/crop growth parameters including yield, rate of fruit growth, fruit size distribution and fruit quality.

6.2 Results and discussion

6.2.1 Fruit growth rate

Fruit growth during the season in all three treatments followed a sigmoidal curve as illustrated in Figure 6.1. Initially fruit expansion was slow, but increased after the first week of measurements and a sharp bi-weekly incline in fruit size can be observed. During April 2020 no fruit diameter measurements took place due to the nationwide COVID 19 lockdown and a sharp increase in fruit size with all three irrigation treatments can be observed between 49 days after measurements commenced (31st of January 2020) and at 96 days when measurements continued again. After this sharp increase, fruit of all three treatments expanded at a lower rate as fruit was maturing and reaching potential size.

Irrigating the same volume of water daily but over different irrigation cycle lengths seem to have no effect on fruit growth rate as no difference in fruit diameter increase over time was observed. This would imply that with all three irrigation treatments water was equally available for fruit growth regardless the discharge rate and consequently irrigation cycle duration. Prinsloo (2007) recorded differences in 'Nules Clementine' citrus growth rate resulting from different volumes of water applied. The results in this study points toward the idea that volume of water applied during the fruit growth period may play a bigger role on fruit growth rate than the duration of the irrigation cycle itself as the same volume was applied with low application rates, T1-0.4L.h^{-1}, T2-0.7L.h^{-1} and daily conventional ,T3-1.6L.h^{-1}.

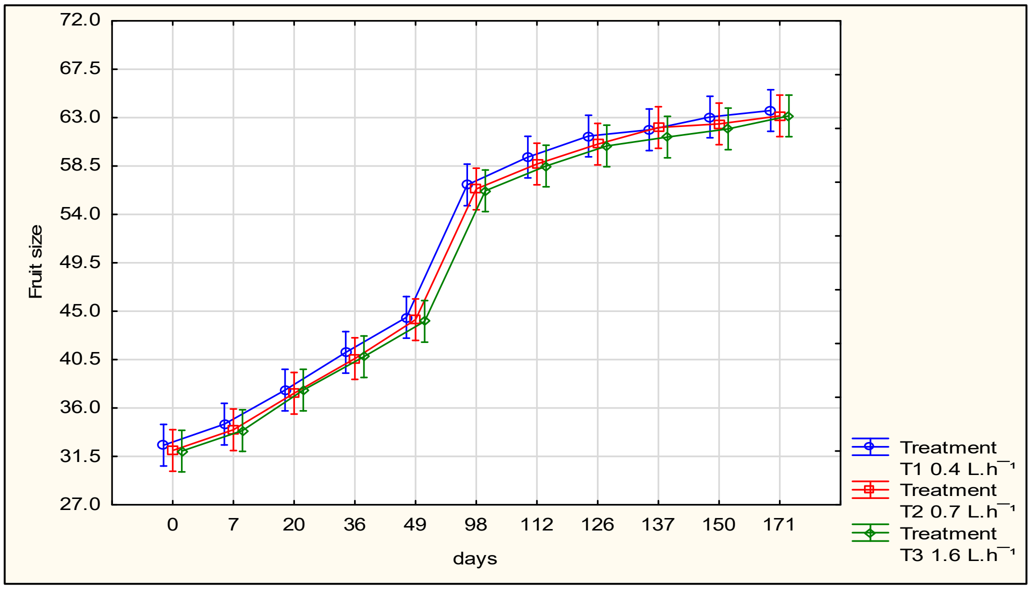

Figure 6.1: Increase of 'Nadorcott' Mandarin fruit diameter as a function of time for each drip irrigation treatment. Vertical bars denote ± SE.

6.2.2 Fruit size distribution

All tree irrigation treatments portrayed a bell shape distribution in fruit size category as illustrated in Figure 6.2, with most fruit distributed over the preferred and highest value fruit size classes (SC) : SC3 (55-59 mm) to SC 1x (68-72 mm) (Cronje, 2016). Percentage fruit allocated within this range of fruit size classes added up to 85.6%, 83.74%, 76.33% for T1-0.4L.h^{-1}, T2-0.7L.h^{-1} and T3-1.6L.h^{-1} respectively. Thus, irrigation from after fruit set until harvest with a lower discharge (0.4L.h^{-1}) resulted in a slightly higher percentage of fruit in the preferred and highest value fruit size class range than irrigation with 0.7L.h^{-1} (T2) discharge and also higher than a daily conventional irrigation regime with 1.6L.h^{-1} discharge rate drippers (T3). This tended lower percentage with T3-1.6L.h^{-1} is due to a slightly more uniformly distribution of fruit across the fruit size classes. As discharge rate decreases the bell shape curve spike more towards the middle as seen in Figure 6.2. All three irrigation treatments tended to have highest percentage of fruit in the SC 2 category although significantly higher percentage was observed with T1-0.4L.h^{-1} compared to T2-0.7L.h^{-1} and T3-1.6L.h^{-1}. Percentages in this class equalled 36.4%, 26.27% and 28% respectively. These results are not obtained from strip picking the trees but fruit size distribution from fruit measured on the tree, randomly selected in the middle window of the tree and therefore give an indication of expected fruit size distribution where in significant differences were found.

Daily conventional irrigation (T3-1.6L.h^{-1}) resulted in significantly higher percentage (12.67%) fruit in the SC 1xx category than low discharge irrigation of T1-0.4L.h^{-1} (7.87%) but it was not significantly different compared to T2-0.7L.h^{-1} (10.67%).

It seems as if applying the same volume of water but distributed over a longer time via low discharge rates tended in a higher percentage of fruit within the preferred fruit size class range. This may be due to higher soil water content levels maintained over time as discussed in Chapter 3, but these results are only from one season (2019 -2020) and do not strongly support such a conclusion. The amount of fruit loss during fruit drop was not taken into consideration and may have influenced the data as fruit drop between treatments may have differed.

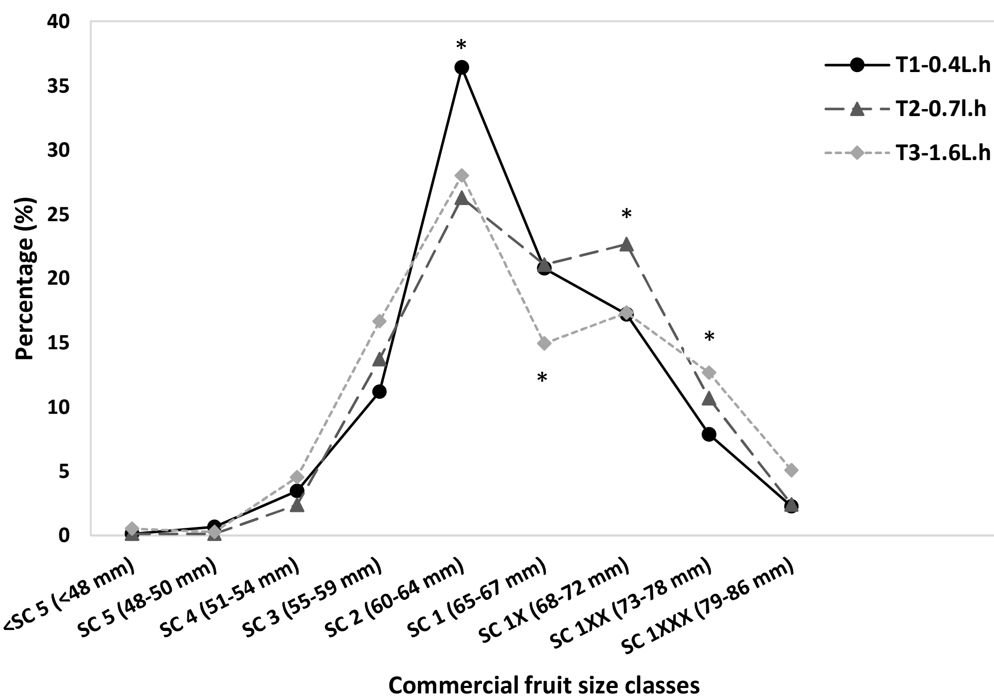

Figure 6.2: Distribution of commercial fruit size classes of 'Nadorcott' mandarin at the time of harvest (August 2020) resulting from three drip discharge irrigation treatments. Data are expressed as means of 15 replicates; * denotes significant differences at the 5% level.

6.2.3 Yield

Applying water continuously at a low rate had no significant influence on yield although differences was observed between the treatments. Because the change in irrigation only took place in November, after fruit set, the average amount of fruit on the trees in each experimental plot were expected to be the same as fruit set occurred under the control treatment T2-0.7L.h^{-1} and therefore differences in yield probably only reflect fruit size differences. The lowest application rate (T1-0.4L.h^{-1}) and hence the longest irrigation hours tended to have a higher yield followed by T3-1.6L.h^{-1} and T2-0.2L.h^{-1} respectively. Average yield in kg/tree was 43.67, 38.45 and 41.89 kg for T1-0.4L.h^{-1}, T2-0.7L.h^{-1} and T3-1.6L.h^{-1} respectively. This amounted to about 34.9, 30.8 and 33.5 tons per hectare. Highest yield in T1-0.4L.h^{-1} may be ascribed to a high percentage of fruit allocated in one fruit size class (SC 2) compared to T2-0.7L.h^{-1} and T3-1.6L.h^{-1}. Different percentages of fruit drop could've also influenced yield differences between irrigation treatments but is unknown as fruit drop per treatment was not determined.

Interesting to note that the treatment under which the orchard was established tended to have the lowest yield, thus the sudden change in irrigation when the treatments was applied, that influenced the soil water distribution, could point to yield differences. More yield data is needed to study the effect of continuous low flow drip irrigation on 'Nadorcott' mandarin production.

6.2.4 Fruit quality

At the end of the 2019/2020 season, fruit quality was not affected significantly by the irrigation treatments. Applying water at a very low rate T1-0.4L.h^{-1} resulted in a tendency of average lower sugar/acid ratio (10.62) than T2-0.7L.h^{-1} (11.38) and T3-1.6L.h (11.28) (Table 6.1). The sugar acid ratio is often used as a benchmark for export quality fruit. Some have reported that OHS and daily daylight fertigation reduces sugar content due to the greater availability of water and uptake, diluting the sugar which accumulates in the fruit (Prinsloo, 2007). A relatively more diluting effect was observed under T1-0.4L.h^{-1}, which also was the treatment that maintained the average highest SWC in the active root zone across the season. Although slightly lower sugar content (expressed as °Brix) was reported under T1-

0.4L.h^{-1} (12.36), all three treatments points to relatively high sugar contents as reported by others under water deficit conditions (García-Tejero *et al.*, 2010; Panigrahi and Srivastava, 2016). °Brix recorded in T2-0.7L.h^{-1} and T3-1.6L.h^{-1} were 13.19 and 13 respectively. It is well known that water stress increases sugar content of fruit. A tendency of higer titratable acidity was reported with T1-0.4L.h^{-1} followed by T2-0.7L.h^{-1} and T3-1.6L.h^{-1} respectively. Thus, a trend of increasing acid with decrease in discharge rate was observed.

Lowest average water content in the active root zone over time in this study was observed with T3-1.6L.h^{-1} which showed a tendency of lower acidity and high sugar content. T3-1.6L.h^{-1} also resulted in average higher juice content (51.1%) followed by T1-0.4L.h^{-1} (49.8%) and T2-0.7L.h^{-1} (49.1%) respectively. Interesting to note that the treatment with average lowest seasonal water content in the active root zone tended to have the highest juice percentage compared to low flow treatments maintaining an average 'wetter' active root zone. Thus, despite lower average SWC in the active root zone in T3-1.6L.h^{-1}, water was still easily available. Differences in all quality parameters reported in this study were not statistically significant.

Table 6.1: Yield and juice characteristics of 'Nadorcott' mandarin at the time of harvest (August 2020) in each drip irrigation treatment. Data represent 10 replicates with 12 fruit per replicate.

Treatment	Yield (kg.tree^{-1})	Sugar (°Brix)	Titratable acidity (TA)	Juice %	Sugar/Acid ratio
T1- 0.4 L.h^{-1}	43.67 ± 9.48	12.36 ± 0.57	1.175 ± 0.113	49.8 ± 3.52	10.62 ± 1.2
T2- 0.7 L.h^{-1}	38.45 ± 7.69	13.19 ± 1.39	1.166 ± 0.09	49.1 ± 2.92	11.38 ± 1.67
T3- 1.6 L.h^{-1}	41.89 ± 7.04	13 ± 1.21	1.158 ± 0.104	51.1 ± 4.38	11.28 ± 1.26

*Although trends were observed, none of the fruit quality parameters reported were significantly different (p< 0.05)

6.3 Conclusion

Applying the same volume of water in different continuous irrigation cycle lengths, via different emitter discharge rates did not affect fruit growth rate. All three treatments followed the same rate in increase of fruit diameter as the season continued. This may indicate that volume of water applied is a more important factor in fruit growth rate rather that irrigation cycle lengths. Applying the daily water requirement over a longer continuous irrigation cycle as with T1-0.4L.h^{-1} and T2-0.7L.h^{-1} seem to increase the percentage of fruit allocated in the preferred and highest value fruit size classes. This trend was more pronounced with ultra-low flow drip irrigation and significantly higher percentage of fruit was distributed in the fruit SC 2 category. Ultra-low flow drip (T1-0.4L.h^{-1}) also increased the fruit weight per tree but it is uncertain if the higher yield per tree is due to fruit size distribution differences or less fruit drop as fruit drop was not considered. Although not significant, the daily conventional irrigation treatment (T3-1.6L.h^{-1}) also had average higher yield per tree than T2-0.7L.h^{-1} (control) and may indicate that the sudden change in irrigation in November 2019 that took place after fruit set, resulting in different water distribution patterns may have caused the trees to respond differently in terms of yield.

No significant differences in fruit quality were observed but applying the water at a very low rate (T1-0.4L.h^{-1}) led to an average lower sugar to acid ratio due to lower sugar content and higher acid percentage. This may be ascribed to a dilution effect resulting from an average higher SWC maintained in the active root zone during the season. The control treatment (T2-0.7L.h^{-1}) tended to have a higher sugar content and sugar to acid ratio. Interestingly T3-1.6L.h^{-1} which resulted in average lower SWC in the active root zone across the season tended to have higher juice % at the time of harvest followed by T1-0.4L.h^{-1} and T2-0.7L.h^{-1} respectively. This was the same trend that was observed with the yield differences.

The crop response results discussed only represents one season's yield data and differences were not significantly different (*p*<0.05). More data is needed to support findings as 'Nadorcott' mandarin is prone to alternate bearing which is expected to influence yield and fruit size distribution. Overall, all three treatments produced expected yields for young 'Nadorcott' trees and satisfactory fruit quality.

Chapter 7: General conclusion and recommendations

Low flow and ultra-low flow continuous drip irrigation is a fairly new concept in the agriculture industry and not a lot of research-based results regarding the soil and crop behaviour are available. In this study we were able to monitor the seasonal soil water content fluctuation between different drip discharge irrigation treatments with various Decagon sensors and EM50 data loggers. This plotted data visually portrayed the behaviour of soil water content at different depths in the root zone along the season and during high evaporative demanding periods with change in application duration due to different drip discharge rates. The difference between treatments seems to occur closer to the soil surface. Ultra-low flow drip (T1-0.4L.h^{-1}) maintained a higher soil water content in the active root zone throughout the season (at field capacity), followed by the low flow drip irrigation (T2-0.7L.h^{-1}) and the daily conventional drip irrigation treatment (T3-1.6L.h^{-1}), although the same volume of water was applied daily.

The Diviner 2000 capacitance probe were successfully used to measure spatial soil water content distribution around a dripper. Installation of PVC tubes in a grid around an emitter for manual probe readings, made it able to visualize 2-dimensional soil water content variation in the root zone during the day across and parallel with the ridge.

2-Dimensional water distribution patterns parallel and across the ridge showed that T1-0.4L.h^{-1} resulted in a smaller wetted soil volume compared to T2-0.7L.h^{-1} with less horizonal and vertical water distribution from an emitter. More overlap was observed in T2-0.7L.h^{-1} parallel with the ridge resulting in greater vertical distribution of water between two adjacent drippers where wetted soil volumes merged. A wetted strip was formed under T3-1.6L.h^{-1} due to narrower spacing of drippers in the drip line compared to the 'pots' formed with T1-0.4L.h^{-1} and T2-0.7L.h^{-1}. Overall, very little fluctuation of the wetted soil volume was observed on a daily basis. However, a bimodal distribution of water was observed in T1-0.4L.h^{-1} and T2-0.7L.h^{-1} early in the morning when a shorter irrigation event took place characterized by a main wetted soil volume in the upper 50 cm and concentrated areas of higher soil water content in the lower 50 cm. Approaching midday as irrigation continued, SWC in the main core of the wetted soil volume increased and lower SWC was observed in the rest of the soil profile indicating a ‘shrinking’ of the wetted bulb at midday, after which a bimodal water distribution resumed. T3-1.6L.h^{-1} showed verry little daily fluctuation.

The PVC tubes installed in the sandy soil unfortunately allowed preferential water flow along one pipe in T3-1.6L.h^{-1} which should be addressed in future studies in similar conditions. A very good winter with average higher rainfall postponed a lot of the measurements as the thoroughly wetted soil profile took a while to dry out. In future studies, automatic probes to measure spatial soil water content distribution would be very beneficial, allowing more readings at shorter intervals and to visualize what is happening with the water during night-time and night-time irrigations.

The root studies showed that citrus fibrous roots can adapt quickly to changes in irrigation regimes and will grow where the root zone environment is favourable. Although the profile method is destructive and very time consuming, it was successful to visually observe spatial root distribution. Applying the daily water requirement at a very low rate (T1-0.4L.h^{-1}) seem to allow roots to grow closer to the soil surface. T1-0.4L.h^{-1} also resulted in roots growing closer to the tree and not spreading across the profile as much as the other treatments did. T2-0.7L.h^{-1} allowed roots to spread across the profile with an increase in roots growing between trees which could be due to more overlap of the wetted soil volumes. The daily conventional drip treatment (T3-1.6L.h^{-1}) resulted in a relatively shallow band of roots growing across the profile, in conjunction with the wetted strip formed due to merging wetted soil volumes.

Fruit quality parameters between the three treatments showed no significant difference, but interesting trends were observed. Ultra-low flow drip irrigation had the highest yield, measured in kg per tree, followed by T3-1.6L.h^{-1} and T2-0.7L.h^{-1} respectively. It is unsure if differences in yield may have been due to a difference in the extent of fruit drop, as this was not quantified and could be a research objective for future studies, or whether it was due to differences in fruit size. More yield data is needed as the ‘Nadorcott’ mandarin is prone to alternate bearing. Applying water at a very low rate (T1-0.4L.h^{-1}) resulted in an average lower sugar/acid ratio due to the lower sugar and higher acid content. The highest sugar/acid ratio was recorded with T2-0.7L.h^{-1}, followed by T3-1.6L.h^{-1}. Thus, a more diluting effect was observed with T1-0.4L.h^{-1}, which was the treatment that maintained the highest SWC in the active root zone along the season. Irrespective of the differences, the sugar acid ratios in all three treatments were high and indicative of good quality fruit. Applying the daily water requirement over a longer continuous irrigation cycle as with T1-0.4L.h^{-1} and T2-0.7L.h^{-1} seem to increase the percentage of fruit allocated in the preferred and highest value fruit size classes. This trend was more pronounced with ultra-low flow drip irrigation and significantly higher percentage of fruit was distributed in the fruit SC 2 category. This was quantified only from fruit allocated in a certain window on the tree and not from the total number of fruits on a tree. In future studies this should be calculated from the total number of fruits on a tree to strengthen the results. Continuous drip irrigation via the three discharge rates had no effect on fruit growth rate.

The results from this study showed that ultra-low, low flow and daily conventional drip irrigation can grow and produce a high value crop. All three irrigation treatments allowed for sufficient root growth to sustain healthy trees. The differences in the soil water content distribution emphasize the importance to know the soil-water behaviour with different irrigation methods and to manage accordingly. The greater overlap of the wetting zones observed in T2-0.7L.h^{-1} imply that drippers could even be spaced further apart in the drip line, under these conditions of the trial.

The results obtained in this study show the importance to proceed with similar studies to highlight the key areas where irrigation-based crop production can benefit from ultra-low and low flow drip irrigation and areas to further improve irrigation management with low flow drip irrigation systems.

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Appendix

Calibration of Decagon sensors

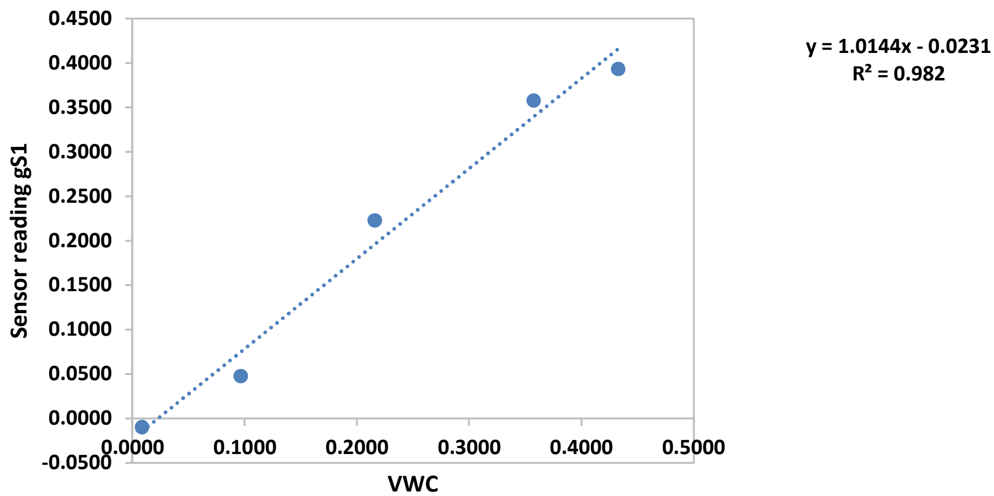

Figure A1.1: GS1 soil moisture sensor calibration curve

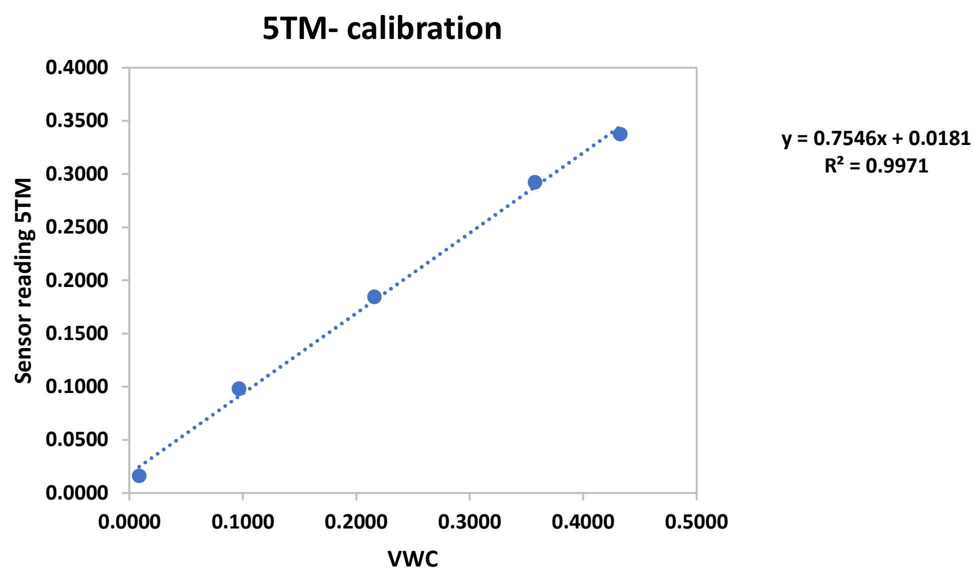

Figure A1.2: 5TM soil moisture sensor calibration curve

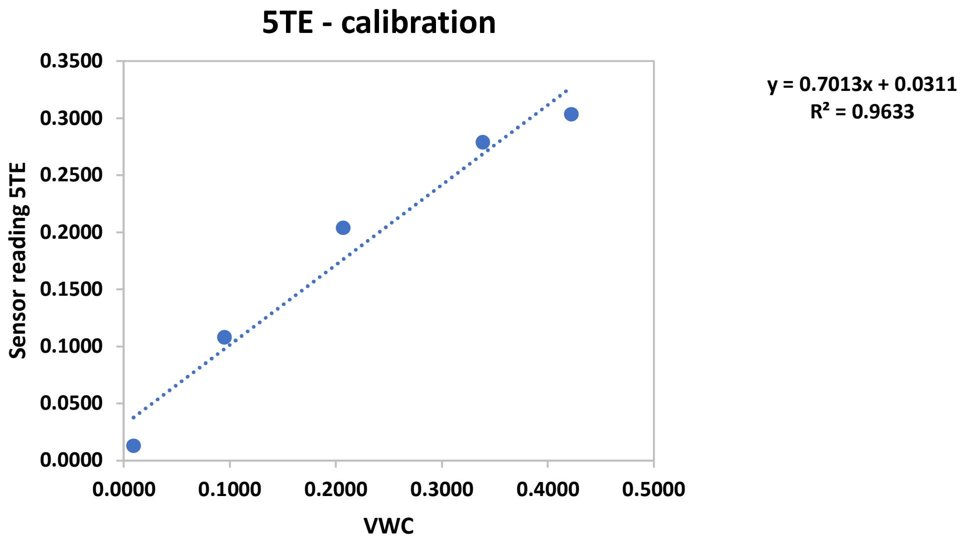

Figure A1.3: 5TE soil moisture sensor calibration curve

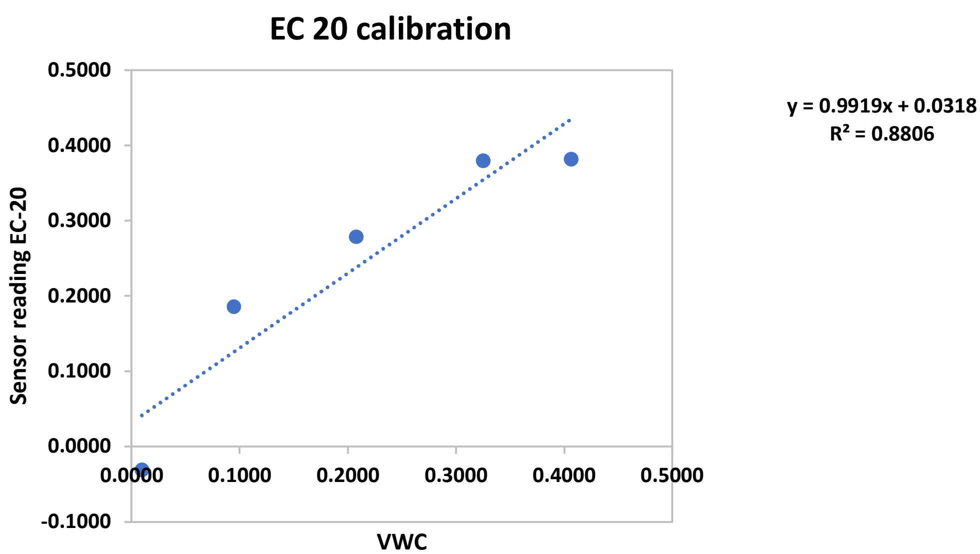

Figure A1.4: EC20 soil moisture sensor calibration curve

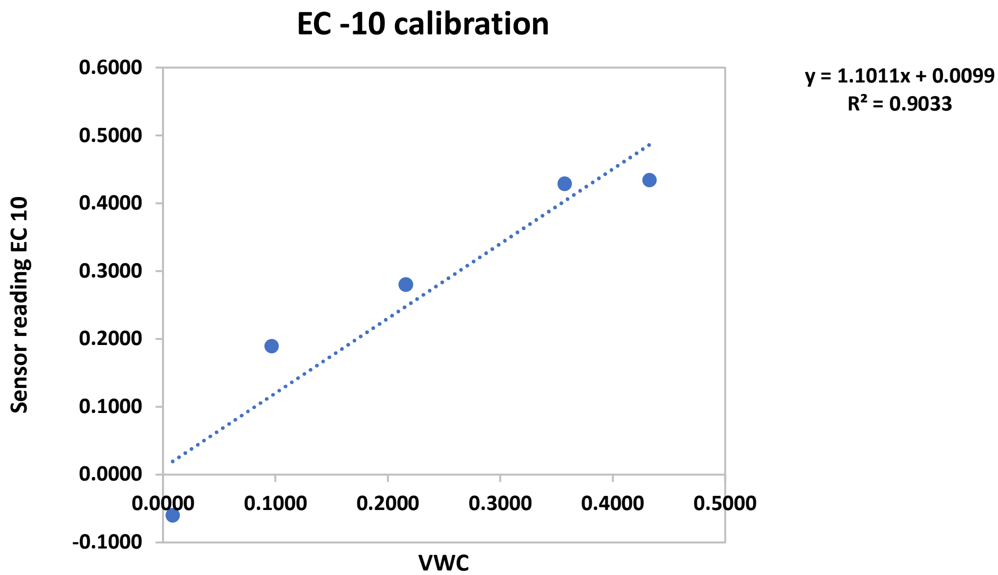

Figure A1.5: EC10 soil moisture sensor calibration curve

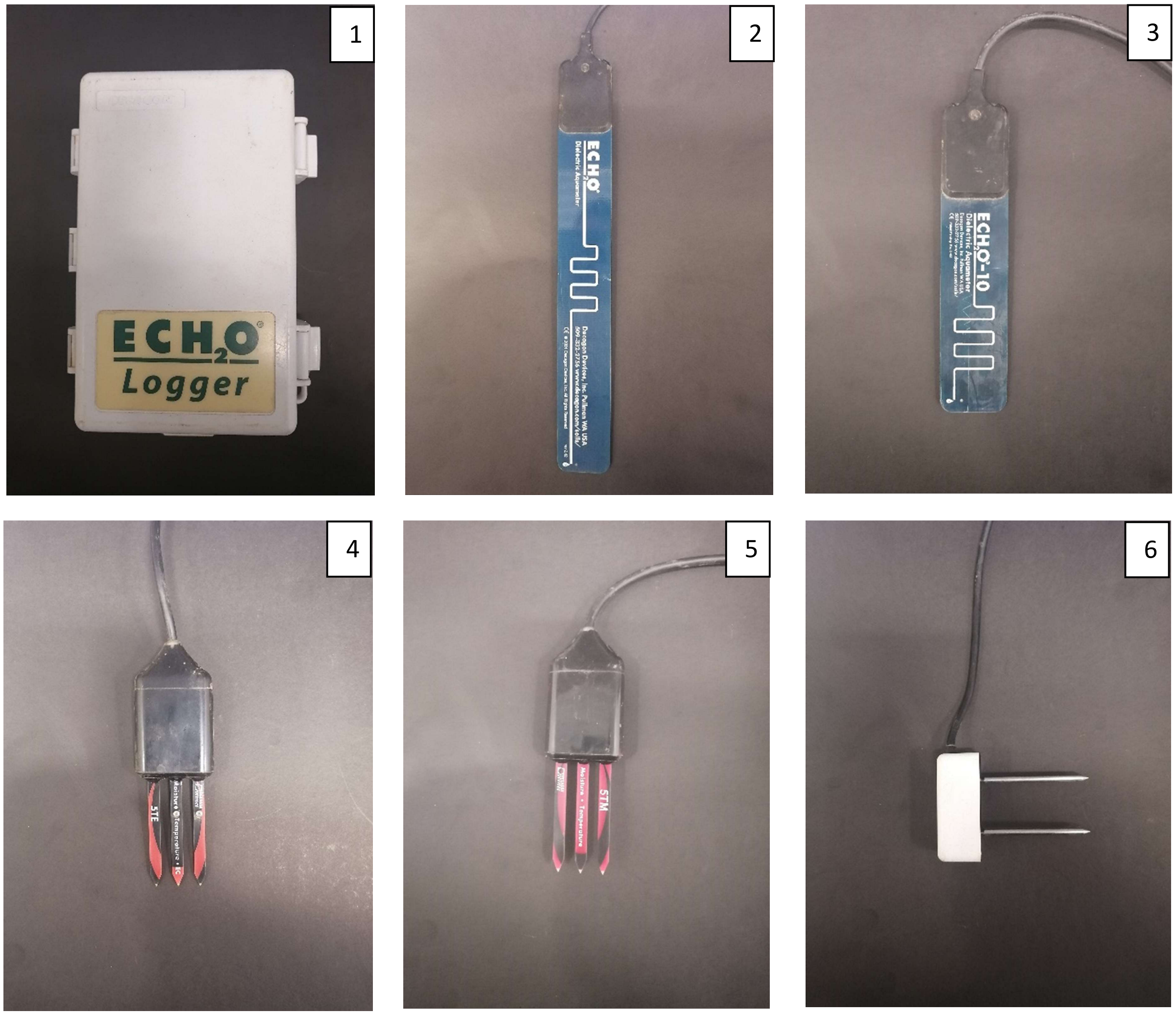

Figure A2: Decagon soil moisture sensors used in this study to monitor the seasonal SWC fluctuation in and below the root zone - Em50 data logger (1), EC20 soil moisture sensor(2), EC10 soil moisture sensor (3), 5TE soil moisture/temperature sensor (4), 5TM soil moisture/temperature sensors (5), GS1 soil moisture sensor (6).

Figure A3 (1&2): Profile pits to quantify root growth and distribution of T1-0.4L.h observed during root studies in October 2020.

Figure A4 (1&2): Profile pits to quantify root growth and distribution of T2-0.7L.h observed during root studies in October 2020.

Figure A5 (1&2): Profile pits to quantify root growth and distribution of T3-1.6L.h observed during root studies in October 2020.