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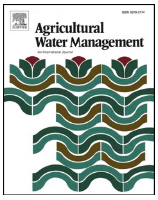

Effects of the number of drip laterals on yield and quality of apples grown in two soil types

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ABSTRACT

The effects of water distribution patterns in drip irrigation on fruit production and fruit quality were evaluated during two seasons in two commercial orchards of Gala Brookfield apple trees, grafted on M.9 dwarf rootstock. Research was conducted at El Manzano farm, with a clay-loam soil irrigated three times per week, and in Santa Mercedes farm, with a stony loam soil irrigated daily. Both farms are located in the Central Valley of Chile. The farm irrigation system was modified to establish three treatments which differed in the number of drip laterals per row (one, two and four), with 4.0, 2.0, and 1.0 L h^{-1} emitters spaced at 50 cm in both farms, respectively. All treatments received the same amount of water per week in each farm, based on the technical criteria of the farm advisor. Applied water in each farm was compared against the water use estimated by the AQUASAT platform. In the clay-loam soil, the volume of applied water was similar to the AQUASAT estimate. However, in the stony loam soil applied water was less than that estimated by AQUASAT. The results showed significant differences in production among treatments which varied only in the volume of wetted soil. The best results pooled over the two years were obtained with one lateral per row (T1) in the clay-loam soil (yield of 59.3 t ha^{-1}), and with four laterals per row (T3) in the stony loam soil which yielded 50.8 t ha^{-1}. Higher yields were associated with a tendency of greater fruit numbers per tree in both farms. Fruit quality requirements for export (equatorial diameter > 60 mm, weight > 90 g) were achieved but not the firmness in the second season at the stony loam soil, due to an irrigation deficit. Our results in apple emphasize the need to wet sufficient soil volume under drip irrigation, regardless of irrigation amounts, in light textured soils in particular.

1. Introduction

Apples are an important fruit crop grown in Chile for export and they are the second most exported fruit in the country. In the Maule region, the red apple production area is 18,706 ha and nationally it is estimated to be 29,168 ha. The area of red apple grown with drip irrigation is 4863 ha and of Gala Brookfield (Baigent apple Brookfield® Gala) is 1443 ha, where nearly 80% of apples grown are intended for export (ODEPA--CIREN, 2016). Among the strategies to compete in world markets, the availability of new apple varieties is critical, as it places the country in a privileged position, in terms of export, as compared to its competitors (Grau, 2015).

The Gala Brookfield apple is known for being of good quality and having an attractive red color and uniformly distributed grooves. Furthermore, at present, the high-density crops systems grafted in the M.9 dwarfing pattern, where the greatest root activity is found in the superficial layers, are being promoted (Foster et al., 2016; Yuri et al., 2011; Kviklys et al., 2012). This results in smaller trees, better management, greater production and easier harvest. The reduction in root system size by using dwarfing rootstocks has implications when drip irrigation is used under high evaporative demand, as there must be a minimum wetted soil volume below which water stress will develop despite supplying full amounts of water. Girona et al. (2010) found that the yield in apple trees grafted onto dwarfing M.9 rootstock, growing in loam soil, was greater with one-dripper per tree due to less evaporation from soil and to deeper infiltration in the soil profile than with two

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drippers per tree. However, the positive effects of increasing the wetted volume of soil in almond trees were shown by Espadafor et al. (2018). In their work, even when water supply was not limiting, almond trees exhibited an enhanced growth and transpiration response when the volume of wetted soil was increased. García-Tejera et al. (2017) have shown with a simulation model of olive that in drip irrigated trees, transpiration can be limited by the wetted soil volume. In addition, they established that the irrigation design should consider that under conditions of low availability of irrigation water, the wetted area of soil should be limited to minimize evaporation losses. On the other hand, there is some evidence that increased soil wetting volume results in higher yields (Morales et al., 2010 in peach; Garcia Petillo and Castel, 2004, in citrus). Holzapfel et al. (2015) studied the effect of the number of laterals per row and irrigation frequency in drip irrigated blueberries, where the use of four laterals per row in a sandy soil resulted in higher production and fruit quality than two and six laterals per row, all applying the same amount of water per bush. As all fresh fruits, apples are primarily composed by water and fruit growth is most affected when trees are subjected to water deficits, which can significantly reduce fruit size (Mpelasoka et al., 2001a, 2001b; Leib et al., 2006). Due to the shortage of water resources available for agriculture, more efficient irrigation strategies are needed to optimize the use of water in apple trees (Leib et al., 2006; Talluto et al., 2008; Girona et al., 2010; Naor, 2014; Zhong et al., 2019), considering that water stress is an important factor that can limit plant performance during the initial phases of growth and orchard establishment (Psarras and Merwin, 2000). As for apple quality, water deficits can increase the concentration of soluble solids (Mpelasoka et al., 2001a, 2001b; Leib et al., 2006). Also, pulp firmness increases as the amount of water applied is reduced (Fallahi et al., 2010). Additionally, pre-harvest climatic conditions may affect fruit diameter, but this is not necessarily correlated with appropriate fruit maturity (Feippe, 1993). Drip irrigation in high density apple tree orchards generally uses one to two emitter laterals per row (Li et al., 2002; Naor, et al., 1999). Therefore, an analysis of the relationship between production and fruit quality with respect to the soil wetting pattern for the same volume of water applied is an important and necessary factor to evaluate, especially given the importance of root distribution in apples.

The aim of this study was to evaluate the effects of water distribution in drip irrigation on fruit production and fruit quality of Gala Brookfield apple grafted on M.9 dwarf rootstock, in two locations with different soil conditions: El Manzano farm (clay-loam soil) and Santa Mercedes farm (stony loam soil).

2. Materials and methods

2.1. Site description

The experiment was performed in a commercial orchard at El Manzano (clay-loam soil) and Santa Mercedes (stony loam soil) farms. Both farms have cv. Gala Brookfield, grafted on M.9 dwarf rootstock, with cv. Granny Smith as pollinator, and were planted in 2012 in an area of 17 ha in El Manzano farm and 8 ha in Santa Mercedes farm, in Río Claro and Molina County located in the Central Valley of Chile (Fig. 1). El Manzano farm is located at the latitude 35°14’19.01" S and longitude 71° 16’ 43.84" W, altitude 267 m a.s.l. Santa Mercedes farm is located at latitude 35°8′18.33" S and longitude 71°15’16.91" W, altitude 277 m a.s.l. and they are located 11 km apart. Both farms have a Mediterranean marine climate with an average annual temperature of 14.9 °C, an average maximum temperature of 30.8 °C in the warmest month (January) and a minimum average of 3.8 °C in the coldest month (July). The frost-free growing period is 7 months, from October to April. The annual sum of temperatures with a base of 5 °C is 3598°-day and 1854°-day with a base temperature of 10 °C. The cold hours from March to November are 1018. Average annual precipitation is 735 mm, with June being the rainiest month with an average of 189 mm. Pan evaporation reaches 1108 mm per year with a maximum of 215 mm/month in January and a minimum of 19 mm/month in June. The dry season is approximately 4 months long and lasts from December to March (Del Pozo and Del Canto, 1999).

2.2. Experimental orchard

Apple trees were spaced 1 m apart in the row and 3.5 m between rows, with an east-west orientation. The agronomic management was provided by COPEFRUT Company (www.copefrut.cl) following the standards of high-density orchards (winter pruning, fertilization, weed control, pest management, and chemical and manual fruit thinning in order to leave a fruit load of 100–120 fruits/tree). Fertigation was used

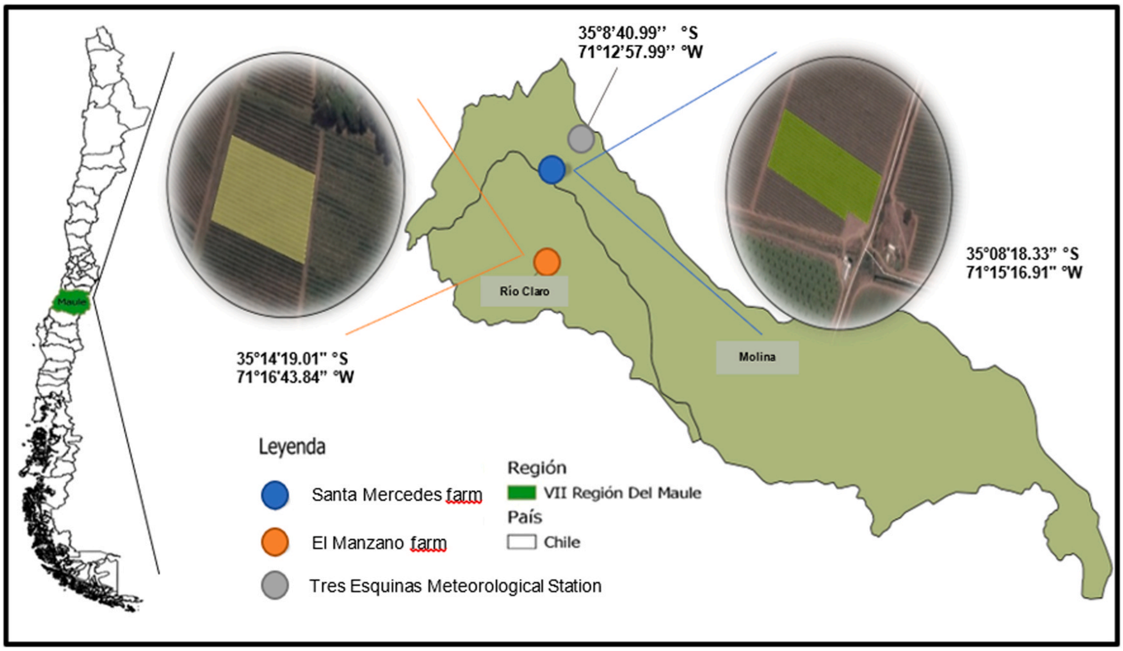

Fig. 1. Geographic location of El Manzano farm and Santa Mercedes farm.

in both orchards throughout the two irrigation seasons (October-March) in weekly applications for a total annual rate of 25 kg ha^{-1} CO $(NH_2)_2$, 44 kg ha^{-1} H_3PO_3, 187 kg ha^{-1} KCl, 126 kg ha^{-1} Ca $(NO_3)_2$, 174 kg ha^{-1} $MgSO_4$. Furthermore, it was supplemented at an annual rate of 15 L ha^{-1} with foliar fertilizer Extra Bioplus (total amino acids: 49%, free amino acids: 20%, organic nitrogen (N) 7.5%, organic carbon 22%, calcium (CaO) 0.3%, potassium (K) 1000 ppm, 17.5 kg ha^{-1} $NH_4H_2PO_4$, 2 L ha^{-1} Amazinc 600 (Zn 35% w/v and Mn 25% w/v), every 7–10 days from October to December, and 9 kg ha^{-1} $CO(NH_2)_2$ plus 15 kg ha^{-1} $MgSO_4$ with three applications every 7–10 days from November to March).

The training system was the Tall Spindle position, and winter pruning in the high density orchards took place during the third or fourth year for precocity and productive centers near the trunk, where the height of the tree was limited to 3.2 m.

The soil physical parameters were determined by the pressure plate method (Klute, 1986) on soil dry mass basis, at pressures of 0.03 and 1.5 MPa. El Manzano farm has soil with a clay-loam texture (Fluventic Humic Dystroxerepts), surface slope about 0.5% to the west and a field capacity ranging from 0.24 g g^{-1} on the surface to 0.23 g g^{-1} at the 0.9 m depth, and a permanent wilting point of 0.13 g g^{-1} throughout the profile. Santa Mercedes farm has a homogeneous soil profile of loamy texture (Aquic Durixerolls) with a field capacity of 0.24 g g^{-1} and permanent wilting point of 0.10 g g^{-1}, a surface slope about 0.4% to the south, with 50% stones in the soil matrix that greatly reduces the water holding capacity. No water table was observed down to 2.0 m at both farms during the two irrigation seasons.

2.3. *Experimental design*

Prior to this study, both farms used drip irrigation with two laterals per row and 4 non-pressure compensating emitters of 2 L h^{-1} per tree. The 2014–2015 season was used as an adjustment period to avoid carry over effects, as the irrigation system was modified in the spring of 2014. Experimental seasons were 2015–2016 and 2016–2017. For each type of soil, a completely randomized block experimental design was established, with three treatments and four replicates. Each individual block consisted of 9 rows of trees. The experimental unit per treatment consisted of three contiguous rows of 40 trees each with a central measuring row and two guard rows. Ten trees in each central row per plot were identified for the two seasons of analysis, for a total of 30 trees sampled per block (three treatments), and a total of 120 trees measured in each orchard. The 12 experimental plots were located in a 0.5 ha area within the commercial orchard at both farms. Blocks were established across rows with irrigation treatments randomly assigned within each block.

The three irrigation treatments were: one lateral per tree row with drippers spaced 50 cm (two emitters per tree) and flow rate of 4 L h^{-1} (T1), two laterals per tree row with drippers spaced 50 cm (four emitters per tree) and flow of 2 L h^{-1} (T2), and four laterals per tree row with drippers spaced 50 cm (eight emitters per tree) and flow rate of 1 L h^{-1} (T3). This design allows maintaining the same volume of applied water in each treatment but achieving differential wetting patterns.

2.4. *Irrigation management*

In the clay-loam soil (El Manzano farm), irrigation was applied three times a week during the season. In the stony loam soil (Santa Mercedes farm), irrigation took place three times a week in October and November, and daily (from Monday to Saturday) for the rest of the season (December to March). The volume of applied water and the irrigation frequency were determined following the criteria of the technical advisor in both farms.

The theoretical volume of irrigation water required by each orchard management unit on each farm was estimated using an online computational platform called AQUASAT (2016). The AQUASAT platform is a decision support system that allows estimating actual crop evapotranspiration determined from a spatially distributed evapotranspiration map, using a Surface Energy Balance model and internalized calibration (METRIC; Allen et al., 2007) and the Landsat 7 and 8 satellite images, with a spatial resolution of 30 by 30 m. With this information of actual crop evapotranspiration, AQUASAT performed a weekly forecast of orchard water demand based on the Hargreaves and Samani model (Samani, 2000). Even though remote sensing estimates of evapotranspiration for orchards could be less precise, it is important to note that the estimates from AQUASAT are upper limit values. Indeed, Gonzalo-Martín et al. (2017) showed that root mean square errors for evapotranspiration estimates are around 1.5 mm day^{-1}, after assessing the performance of Surface Energy Balance models using satellite images in the Central Valley of Chile. Thus, AQUASAT has shown to be a reliable and useful tool to tailor irrigation management practices by providing for next-days estimates (*ex- ante* estimates) or for *ex-post* assessment (Holzapfel et al., 2020; Gavilán et al., 2019). It must be stressed that AQUASAT evapotranspiration estimates are used as guiding values instead of error-free values of actual crop evapotranspiration. In a review about estimates of actual ET using remote sensing methods, Zhang et al. (2016) discusses the sources and approaches to reduce uncertainties in time and space. They conclude that merging multiple sources would increase accuracy, but not necessarily the understanding of underlying physical process. Also, it is important to note that uncertainty coming from field data at the point scale may not be representative of what is occurring at the field scale.

Weather data were obtained from the Tres Esquinas Meteorological Station (INIA, 2017), located 3 km east from Santa Mercedes farm and 14 km northeast from El Manzano farm. Daily precipitation and minimum and maximum air temperatures for the two experimental seasons are shown in Fig. 2.

2.5. *Soil moisture measurements*

The soil moisture content was determined twice a week with a neutron probe (Troxler Model 4300, NC, USA) that was calibrated at the site (R^2 of 0.88) in the clay-loam soil (El Manzano farm) during the first season. Three access tubes were installed at the treatment sites of one lateral (T1), five access tubes in the treatment of two lateral (T2) and the treatment of four lateral (T3) had seven access tubes, distributed around the trunk, perpendicular to the plantation row (Fig. 3 A). Moisture was measured in soil layers of 0–30, 30–60, 60–90 cm. Each block of the experimental design had a similar access tube arrangement for each treatment, with a total of 12 trees. In the second season, soil moisture content was measured with a set of seven Watermark sensors for depths comprising layers of 0–30, 30–60, 60–90 cm around the root system of a representative tree (Fig. 3B) and in a single experimental unit per treatment. The soil moisture content in the Santa Mercedes farm, due to its 50% stone content, was measured with a set of seven Watermark sensors (Irrometer Company, Inc., CA, USA) for depths comprising layers of 0–30, 30–60, 60–90 cm around the root system of a representative tree (Fig. 3B) and in a single experimental unit per treatment. A datalogger measured the voltage readings of the seven sensors every 30 min. The soil-water tension readings were converted to soil water content values through the individual laboratory calibration of the Watermark sensors. The sensors were placed in a water container for 12 h in order to reach a saturation tension of 0 centibar. Soil samples were sieved at 2 mm mesh and taken to a container where the sensors were positioned at 15 cm depth and 25 cm apart in saturated soil, recording the water tension after sensor voltage readings were stabilized. The extracted soil samples were then placed in an oven at 105 °C temperature for 48 h to obtain the gravimetric moisture content at the respective tensions. Finally, the relation between gravimetric moisture content and soil water tension was determined using a quadratic adjustment. The soil moisture content for both farms was depicted using the Kriging interpolation method (Oliver and Webster, 1990) implemented in Matlab ®.

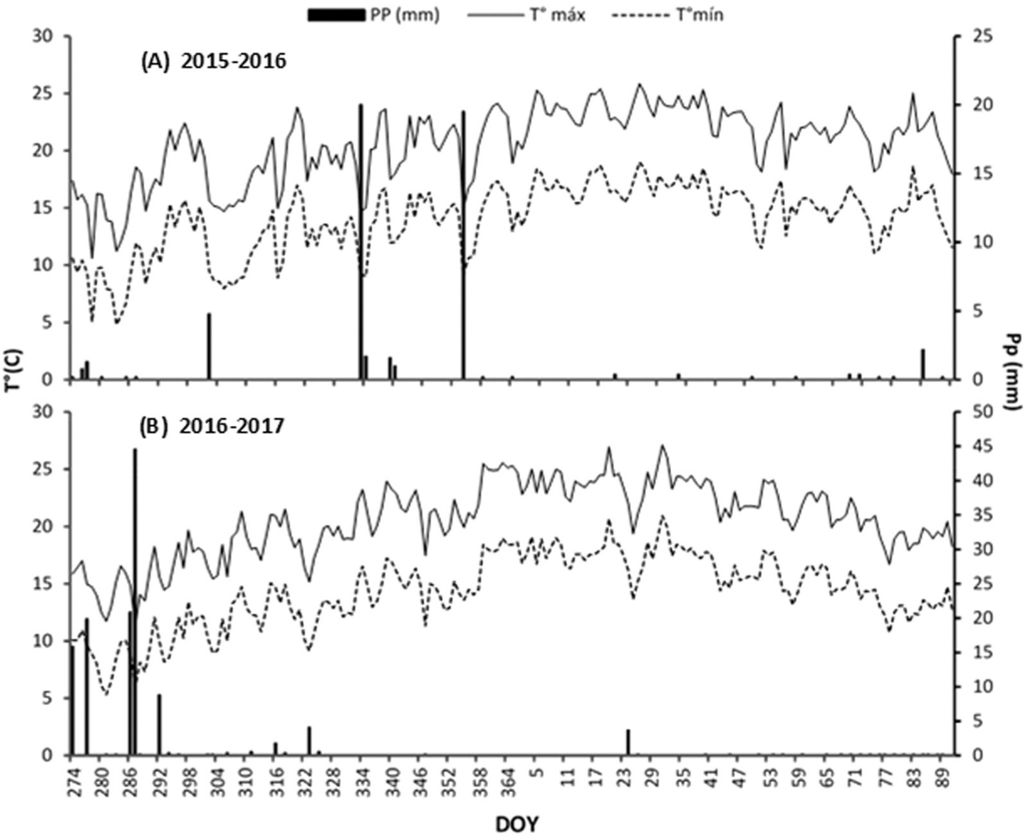

Fig. 2. Daily minimum (mín) and maximum (máx) air temperatures (T°), daily precipitation (Pp) for 2015–2016 (A) and 2016–2017 (B) seasons (INIA, 2017). DOY is the day of year.

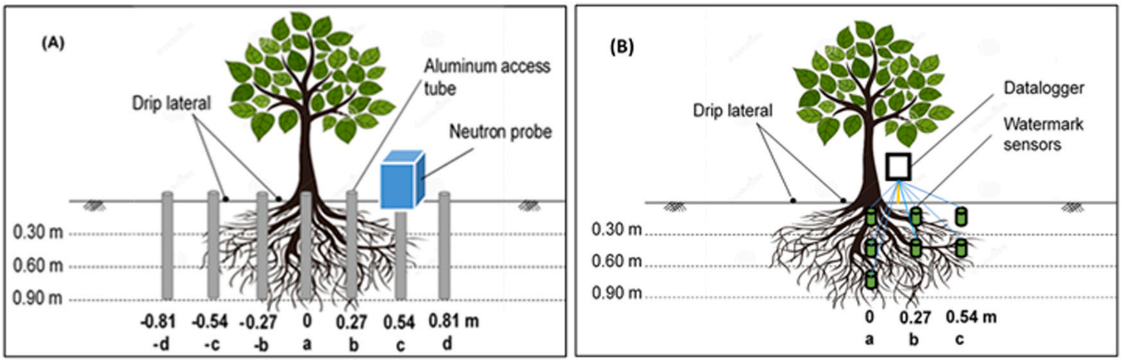

Fig. 3. Arrangement of neutron probe access tubes and Watermark sensors for treatments. Positions: "a" (under the trunk), "b" (27 cm from the trunk), "c" (54 cm from the trunk), "d" (81 cm from the trunk). A: only 2015–2016 season at clay- loam soil (El Manzano farm) and B: 2015–2016 and 2016–2017 seasons at both stony loam soil (Santa Mercedes farm) and 2016–2017 season at El Manzano farm.

2.6. Fruit yield and statistical analysis

The harvest took place in mid-February in both seasons when all the fruits of the 10 trees in the central row of each experimental unit (40 trees per treatment) were harvested. The total harvest weight was obtained using a digital scale with a precision of 0.5 kg. For fruit quality parameters, 30 fruits from each experimental unit were randomly selected and the weight of each fruit was measured with a precision of 1.0 g. The equatorial diameter was measured for each of the selected fruits using a Vernier caliper. Fruit flesh firmness was measured at the equator of each fruit after removing the exocarp (peel), using a manual pressure meter (Effegi FT 327, Italy) with an 11 mm strut. At the time of fruit firmness evaluation, total soluble solids (°Brix) were measured with a refractometer (Atago, model Master-T, Japan).

In January 2017 trunk diameters were measured in 40 trees per treatment at both farms, 15 cm above the graft union. For both seasons and farms, the fraction of soil surface covered by the green canopy was 70% in January.

For each farm, independently, an analysis of variance (ANOVA) was conducted considering separately irrigation treatments and season. The means were compared with Tukey's multiple test ($P \leq 0.05$) using R Project software.

3. Results and discussion

3.1. Applied water

In the 2015–2016 irrigation season at the farm of clay-loam soil, the applied water was very similar to that estimated by AQUASAT (Fig. 4 A). The water volume estimated by AQUASAT was 3187 m^3 ha^{-1} while applied water was 3080 m^3 ha^{-1}, a difference of ca. 3% for the 2016 January to early March period. Similarly, in the 2016–2017 irrigation season (Fig. 4 C), the water volume estimated by AQUASAT was 5066 m^3 ha^{-1} and the water volume applied was 4851 m^3 ha^{-1}, a difference of ca. 4% for the October 2016 February 2017 period. While there were minor variations along the irrigation season, in El Manzano farm there was general agreement between the applied water and AQUASAT estimates of seasonal water requirements.

For the stony loam soil in the 2015–2016 irrigation season (Fig. 4 B), the volume estimated by AQUASAT was 3422 m^3 ha^{-1} while the volume of applied water was 14% less, 2945 m^3 ha^{-1} for the 2016 January to March period. For most of that period, there was an irrigation deficit, even though in February there was an excess of applied water. In the second season (October 2016 to end of February 2017; Fig. 4 D), the water requirements estimated by AQUASAT were 4375 m^3 ha^{-1} while the applied water was 3035 m^3 ha^{-1}, a deficit of ca. 30%. From October until the middle of December, water application was less than that calculated by AQUASAT, and thereafter amounts were similar. Thus, in the Santa Mercedes farm the volume of applied water was insufficient to meet the demand estimated by AQUASAT, particularly in the second season.

Despite the missing data from October to December (2015–2016 season) and given the climatic conditions that concentrate the irrigation season in summer, our irrigation study encompasses the main season in both years and farms and it is highly probable that the picture that emerges from this research will not change. In fact, in spring the soil is still wet from the winter rains and the orchard water requirements are still low. Furthermore, two rains of 20 mm each occurred in December 2015 (Fig. 2A), so the irrigation requirements decreased even more.

It is well known that the timing, extend and magnitude of water deficits / excesses could affect yield and quality at harvest (Kuschel-Otárola et al., 2020a). Even though weekly values are shown in Fig. 4, it must be emphasized that the experimental design was set to assess differences between seasonal applied water and fruit quality at harvest. Even with the detailed data collected, it is extremely difficult to disentangle water stress variations at weekly time-scale as shown in Fig. 4 at Santa Mercedes farm, where there were periods on excess / stress. However, in this regard, AQUASAT provides guidance raising flags when applied water is outside the predefined ranges, leading to water excess / stress.

3.2. Soil water content

Fig. 5 presents representative data on soil water content prior to an irrigation event in the 2015–2016 season for both farms. For the clay-loam soil, T2 and T3 exhibited a gradual decrease in soil water content vertically, and a horizontal variation with maximum depletion at the deeper depths (Fig. 5) under the tree trunk. The low soil water content values observed, close to the permanent wilting point in these two treatments, would indicate a situation of low water availability. However, T1 treatment showed water uptake just in the first 45 cm of depth around the trunk indicating a shallower water extraction pattern. In the stony loam soil, there was increased depletion with depth as the

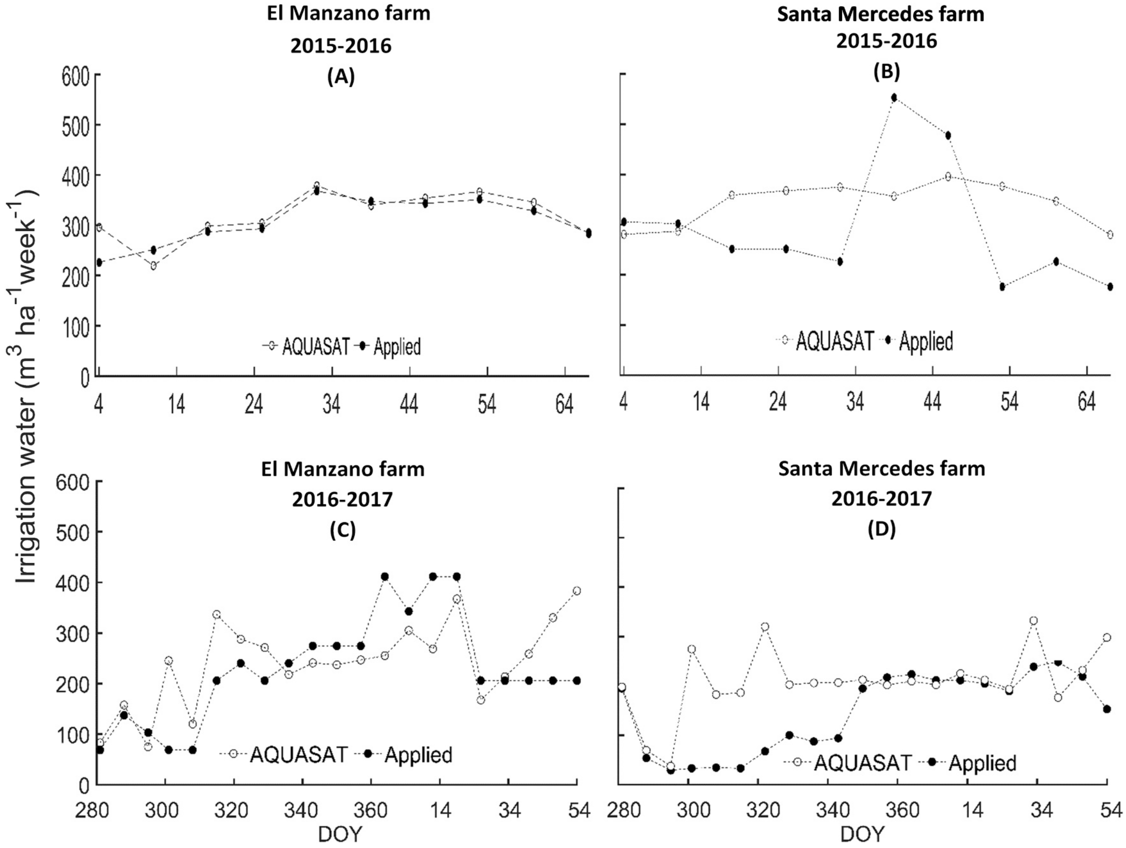

Fig. 4. Irrigation water applied and estimated by AQUASAT during the irrigation seasons 2015–2016 and 2016–2017 at both El Manzano farm (clay-loam soil) and Santa Mercedes farm (stony loam soil). A and B: January – beginning of March 2016 period; C and D: October 2016 – end of February 2017 period. DOY is the day of year.

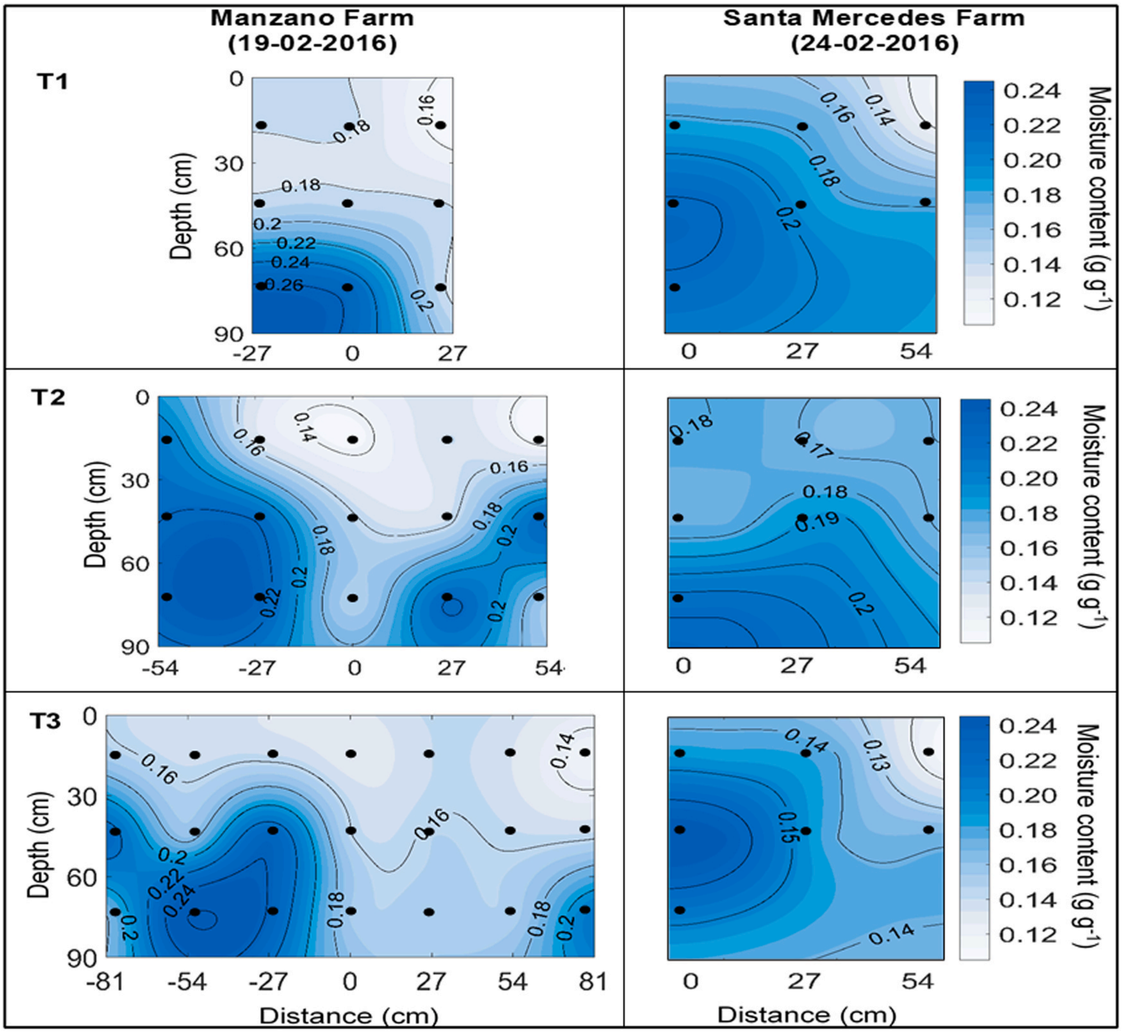

Fig. 5. Behavior of the soil water content distribution in the profile of the clay- loam soil site (El Manzano farm) and the stony loam soil site (Santa Mercedes farm) just before irrigation. The drip irrigation treatments are one lateral per row (T1: two drippers per tree), two laterals per row (T2: four drippers per tree) and four laterals per row (T3: eight drippers per tree). Measurement dates: 19–02–2016 and 24–02–2016. Field capacity is 0.24 g g^{-1} both farms, and permanent wilting point is 0.13 g g^{-1} (clay-loam soil) and 0.10 g g^{-1} (stony loam soil). Black dots indicate reading points of soil water content at 0 cm (under the trunk), 27 cm, 54 cm and 81 cm from the trunk (neutron probe at El Manzano farm and Watermark sensors at Santa Mercedes farm).

number of laterals increased from T1 to T3, as indicated by the lower water content in T3.

The seasonal trend during 2016–2017 of soil water content at two soil depths for the three treatments is presented in Fig. 6. In the case of clay-loam soil, the effects of the different treatments on soil moisture content are clear. For the case of T1, the first two strata in the area near the trunk remained close to field capacity, indicating the expansion of the wet bulb in this type of soil. By contrast, 54 cm away from the trunk, the soil moisture content is monotonically decreasing down to the permanent wilting point. This was probably caused by the combination of root water extraction outside the emitter zone and of evaporation from the unshaded soil. For the T2 treatment and 0–30 cm of soil depth, it is observed that the zone closest to the trunk was maintained at high soil water content. Decreasing soil water content occurred at a distance of 27 cm from the trunk, since the end of December, and at a distance of 54 cm from the trunk since the end of November. At the 30–60 cm of soil depth, the soil water content decreased only at a distance of 54 cm from the trunk. For the T3 treatment, the total soil profile remained with high soil water content, due to the pattern of tree water uptake and the extracting capacity of the root system under a very shallow and wide wetted surface area.

The stony loam soil showed, in general, soil water content variability both vertical and horizontally during October through November (Fig. 6), with high soil water content near the trunk for all treatments in the upper layer. However, since the beginning of December a change of irrigation frequency – from three times a week to daily irrigation - produced an effect on the soil wetting pattern too. In T1, the soil water content at 27 cm distance remained in the range between field capacity and permanent wilting point, a situation attributed to root water extraction. Also, at 54 cm away from the trunk, the soil water content remained practically at permanent wilting point during the entire season, showing that irrigation water did not reach that zone. In the 30–60 cm depth, close to the trunk and 27 cm away, the soil water content was close to field capacity. However, at 54 cm away from the trunk, the soil water content approached permanent wilting point values throughout the irrigation season. In T2, it was observed constant high soil water content near the trunk as well as at 27 cm from it in the upper layer while at 54 cm away from the trunk, the soil water content remained between field capacity and permanent wilting point, probably due to lack of wetting by the emitters and to soil water evaporation. For the 30–60 cm depth, the soil water content remained practically near field capacity for all distances from the trunk through the entire irrigation season. Finally, in the T3 treatment, the soil water content at all distances away from the trunk at all depths stayed near field capacity

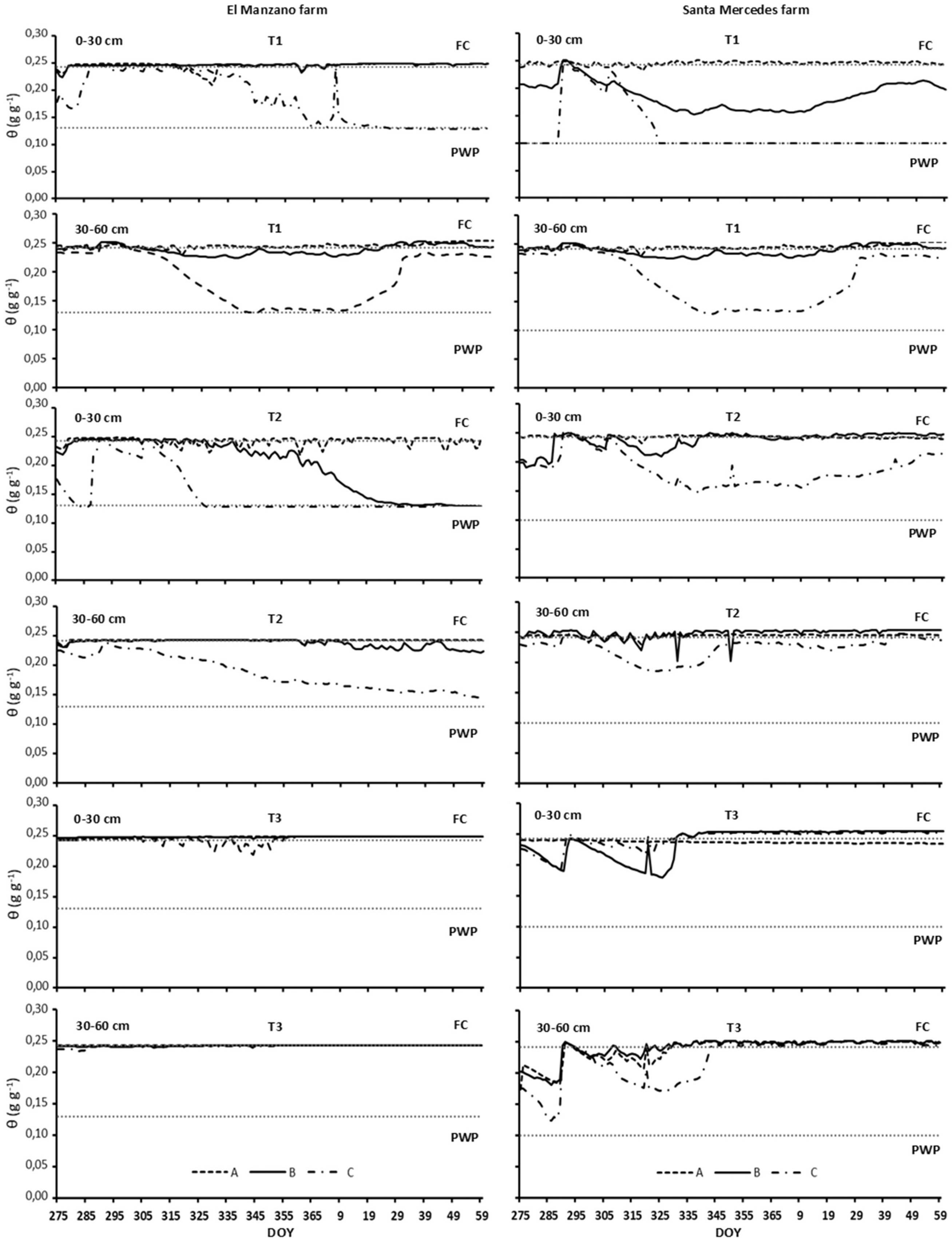

Fig. 6. Seasonal course of the soil water content distribution (θ) at 0–30 cm and 30–60 cm of soil layer depth in the profile of the stony loam soil site (Santa Mercedes farm) and clay-loam soil (El Manzano farm) during the irrigation season 2016–2017. The drip irrigation treatments are one lateral per row (T1: two drippers per tree), two laterals per row (T2: four drippers per tree) and four laterals per row (T3: eight drippers per tree). The reading points of soil water content are: (A) under the trunk), (B) 27 cm and (C) 54 cm from the trunk. DOY is day of year. FC is field capacity and PWP is permanent wilting point.

since the beginning of December.

Girona (2007) found for mature apple trees grafted on M.9 rootstock, growing in a loam texture soil, little water extraction below 40 cm of depth. In addition, Girona et al. (2008, 2010) determined that under extreme drought conditions, reducing the number of emitters per tree from two to one drastically reduced the wetted area, decreasing soil evaporation, thus leaving more water available in the soil profile with a positive effect on yields. Then, it can be concluded that the volume of soil water content in clay-loam soil under T1, would allow adequate soil water content up to a distance of 27 cm from the trunk in the first two layers of soil (0–30 cm and 30–60 cm). On the other hand, in T3 there was high soil water content in the profile (Fig. 6), which is not recommended for the M.9 dwarf rootstock. It is known that M.9 rootstock requires a well-drained soil (Crassweller and Schupp, 2018). In fact, Olien and Lakso (1986) observed, under warm and sunny conditions and high soil moisture, lower midday stem water potential of apple trees grafted on M.9, than in trees grafted on other rootstocks.

In the case of a stony loam soil, the volume of soil wetted in the first 60 cm of depth and up to a distance of 54 cm from the trunk was largely suitable in the T3 treatment since December, associated with the change in irrigation frequency from three times a week in October and November to daily irrigation for the rest of the season. However, it was insufficient for the T1 and T2 treatments. Paltineanu et al. (2017) determined an intense concentration of roots near the tree, with an 80% of roots in the first 60 cm of soil depth and to a horizontal distance of 40 cm on the row and 70 cm between rows, in mature apple trees grafted on M.9, growing in a loamy-sand soil under drip irrigation. Tanasescu and Paltineanu (2004) found, in a loamy-sand texture and under various irrigation methods, maximum values of active roots within the first 40 cm of depth, in Golden Delicious apple grafted on M.M 106 rootstock (semi-dwarfing). For this reason, soils with low water storage capacity tend to have the highest root concentration in the superficial layers of soils, when there is an adequate level of water in such strata. In addition, it is important to point out that the root system requires to obtain the water from an adequate volume of soil that has the capability to provide the water in periods of highest evaporative demand. Fernandez and Perry (1995) in a research with several apple rootstocks (including M.9) in two type of soils found that around 91–94% of roots were localized in the first 60 cm depth in silt loam soil with a fragipan at 60 and 70 cm below the soil surface. However, in soil without any restriction (fine sandy loam), only an average of 60% of roots were in the first 60 cm depth, showing that the root system growth is greatly affected by soil conditions.

The soil moisture data (Fig. 6) confirmed that water deficits developed in the Santa Mercedes farm due to the water applied being less than that predicted by AQUASAT. To compensate for this irrigation deficit in the October to December period (Fig. 4), an active root water uptake was observed, which is reflected in the decrease of soil moisture at T2 and T3 in all distances from the trunk in that period. In the case of T1 this situation was less noticeable.

3.3. Production

The total fruit production shown in Table 1 indicates that, in both seasons, at the clay-loam soil site, the highest yield was obtained in the T1 treatment. This response indicates that sufficient soil volume was wetted with one lateral, probably in the zone of the largest amount of roots water extraction. Fig. 5 showed in T1 that, in this soil, it was possible to wet with one lateral an adequate density of active roots in approximately 60 cm in-depth and a horizontal diameter of 54 cm. The two other treatments (T2 and T3) also wetted more horizontally, but also more superficially than in T1, causing more evaporation from soil. For this clay loam soil, one lateral per row with emitters of 4 L h^{-1} spaced at 50 cm allowed for an application of water that wetted the root water extraction zone in an appropriate way.

Table 1

Apple fruit yield at harvest for treatments of one (T1: two drippers per tree), two (T2: four drippers per tree) and four (T3: eight drippers per tree) laterals per row with drip irrigation in El Manzano farm (clay-loam soil) and Santa Mercedes farm (stony loam soil).

Season/Treatments	Total production (t ha^{-1})	
	Clay-loam soil	Stony loam soil
2015–2016		
T1	54.71	39.34
T2	52.80	38.20
T3	46.48	48.79
2016–2017		
T1	63.88	42.94
T2	59.77	45.59
T3	59.44	52.85
ANOVA/Means		
Treatments (T)	*	***
T1	59.29 a	41.14 b
T2	56.28 a	41.90 b
T3	50.71 b	50.82 a
Season (S)	**	**
2015–2016	51.34 b	42.11 b
2016–2017	59.54 a	47.13 a
T x S	ns	ns

Note: ANOVA: T×S interaction; ns: not significant. Seasons 2015–2016 and 2016–2017. Means followed by different lowercase letters in columns indicate significant differences according to the Tukey test ($P \leq 0.05$).

[*] $p \leq 0.05$.

[**] $p \leq 0.01$.

[***] $p \leq 0.001$.

The fruit production in the stony loam soil was significantly higher in T3 for both seasons (Table 1). This would indicate that wetting a greater soil volume resulted in more effective irrigation, due to the low soil water storage capacity as affected by the presence of stones (50%) in the soil matrix. Conversely, in T1 and T2, the soil water content mostly increased in-depth but the surface layers with the highest density of active roots did not get sufficient water. Thus, T3 wetted a greater soil volume than the other two treatments in the first two layers, where the highest root densities occur (Girona, 2007).

In the second season, there was an increase in production on both farms, even though at Santa Mercedes the water applied was less than what AQUASAT estimated (Fig. 4). Possibly, increased tree growth from the fourth to the fifth year led to greater estimated water requirements. As a comparison, Yuri et al. (2011) obtained average yields around 24.9 ton/ha in a 4-year-old apple tree grafted on M.M.106 (semi-dwarfing) and 42.5 ton/ha in a 5-year-old Brookfield Gala on rootstock M.9 EMLA (dwarfing), in a commercial orchard on a silty clay loam soil. Ortega et al. (2014) in a zone with the same climatic conditions as those of our study, obtained similar yields (58.5 ton/ha) with 6-year-old Royal Gala grafted on rootstock M.26 (dwarfing) in clay loam soil, drip irrigated (two laterals and four emitters per tree), with a 100% reposition of crop evapotranspiration, However, with a 125% reposition of crop evapotranspiration, yield was only 38.70 ton/ha. On the other hand, Yildirim et al. (2016) showed lower yields (42.9 ton/ha) for a 5-year-old Royal Gala grafted on rootstock M.9 in a medium-light-textured soil in Isparta, Turkey, with very heavy crop load, and excess water application (Using a Kp of 1.25 of Class A pan evaporation) under drip irrigation with two laterals and four emitters per tree.

These reports and our results show the importance of maintaining adequate soil moisture distribution conditions of apple trees grafted on rootstock M.9. Thus, soil type and wetting patterns under drip irrigation have an important influence on the yield and performance of trees under different irrigation strategies, as it provides a significant storage and buffer for plants, making it possible to produce “more crop per drop” (Kuschel-Otárola et al., 2020b).

3.4. Fruit quality

For both seasons and soil types (Tables 2 and 3), the fruit equatorial diameters were above the 60 mm minimum required by the Standard Codex Stan 299–2010 (FAO, 2010) for apples, without significant differences between treatments at each farm. However, there was a trend to higher equatorial diameter values in the stony soil in both seasons, probably due to a reduction of fruit numbers, as found by Yildirim et al. (2016).

The weight of the fruit was higher than the 90 g minimum required for export (FAO, 2010) in both seasons and soil types (Tables 2 and 3). Significant differences in fruit weight were not recorded between treatments at each farm, but the fruit weight was significant higher at both farms in the second season.

It is important to mention that the number of fruits is directly related to yield and this variable is highly relevant in commercial production (Yildirim et al., 2016). Furthermore, with optimal pruning as well as agronomic management, larger fruit sizes can be obtained (Parra-Quezada et al., 2008). The trunk diameter is associated with the climatic conditions of the area (Yuri et al., 2011), and the fruit load in the management of the orchards (Barden and Marini, 2001; Yildirim et al., 2016). In January 2017, El Manzano farm recorded a trunk diameter of 5.7 cm (T1 and T2) and 5.5 cm (T3), while Santa Mercedes farm recorded a trunk diameter of 4.3 cm (T1) and 4.6 cm (T2 and T3), without significant differences between treatments at each farm. On the other hand, this average difference of 1.1 cm between the two farms may be an indication of differences in irrigation management that are expressed in fruit number per tree. In our case, the number of fruits per tree at harvest was lower in stony loam soil in both seasons (Table 3). Likewise, the tendency of a greater number of fruits in the T3 treatment for both seasons would explain the greater yield in the stony loam soil when irrigated with four laterals per row. Also, the tendency of the T1 treatment in clay- loam soil towards a higher number of fruits would explain its higher yield (Table 2).

As for fruit firmness, this variable was higher than 76 N/cm^2 (17 lb/cm^2) in the clay-loam soil (Table 2), while the firmness values in the second season in the stony loam soil were below the minimum required for export (Table 3). These results could be related to the deficit irrigation situation that occurred in the stony loam soil, as detected by AQUASAT (Fig. 4 D), especially during initial fruit development stage. On the other hand, Mpelasoka et al. (2001a) reported that late-season deficit irrigation increased firmness in 7-year-old ‘Braeburn’ apple grown in lysimeters and irrigated at 40% of well-irrigated control treatment. On the other hand, Fallahi et al. (2010) with 5-year-old ‘Autumn Rose Fuji’ apple fruits and Talluto et al. (2008) with 5-year-old ‘Lady Pink’ apple fruits shown that fruit firmness at harvest was unaffected by irrigation regimes. Low firmness at harvest and low calcium uptake into the plant is associated to low soil water content and high temperatures during the growing cycle (Milosevic and Milosevic, 2015). Also, several postharvest disorders are related to calcium in apple fruits (Doryanizadeh et al., 2017), and fruit with higher firmness at harvest tend to maintain better conditions after storage than fruit with lower firmness (Johnston et al., 2002).

Table 2
Fruit quality at harvest for the treatments of one (T1: two drippers per tree), two (T2: four drippers per tree) and four (T3: eight drippers per tree) laterals per row in the El Manzano farm (clay-loam soil) in the irrigation seasons 2015–2016 and 2016–2017.

Season/ Treatment	ED (mm)	Fruit weight (g)	Fruit per tree	Firmness (N cm^{-2})	TSS (°Brix)
2015–2016					
T1	68.5	159.3	125	99.0	12.0
T2	68.9	161.2	119	99.2	11.8
T3	69.9	166.4	101	93.1	11.9
2016–2017					
T1	71.3	181.3	135	101.5	12.4
T2	73.3	198.8	128	86.4	12.2
T3	73.0	192.9	125	99.2	12.7
ANOVA/Means					
Treatments (T)	ns	ns	**	ns	ns
T1	69.9	170.3	130 a	100.2	12.2
T2	71.1	178.0	124 a	92.8	12.0
T3	71.5	179.7	113 b	96.2	12.3
Season (S)	+	*	*	ns	**
2015–2016	69.1 b	162.3 b	115 b	97.1	11.9 b
2016–2017	72.5 a	191.0 a	129 a	95.7	12.4 a
T x S	ns	*	ns	***	ns

Note: ANOVA: T × S interaction; ns: not significant; ED: equatorial diameter; TSS: total soluble solids. Means followed by different lower case letters in columns indicate significant differences accordingto the Tukey test (P ≤ 0.05).

[*] $p \leq 0.05$.

[**] $p \leq 0.01$.

[***] $p \leq 0.001$.

Table 3
Fruit quality at harvest for the treatments of one (T1: two drippers per tree), two (T2: four drippers per tree) and four (T3: eight drippers per tree) laterals per row in the Santa Mercedes (stony loam soil) in the irrigation seasons 2015–2016 and 2016–2017.

Season/ Treatment	ED (mm)	Fruit weight (g)	Fruit per tree	Firmness (N cm^{-2})	TSS (°Brix)
2015–2016					
T1	71.8	167.8	86	76.6	11.9
T2	71.2	168.7	88	78.6	12.3
T3	72.1	159.5	105	75.1	12.2
2016–2017					
T1	75.1	200.9	109	66.5	13.2
T2	74.7	196.6	104	67.1	13.3
T3	74.9	196.7	113	74.2	12.8
ANOVA/Means					
Treatments (T)	ns	ns	ns	ns	ns
T1	73.5	184.4	98	71.5	12.5
T2	72.9	182.7	96	72.9	12.6
T3	73.5	178.1	109	74.6	12.5
Season (S)	**	**	**	*	*
2015–2016	71.7 b	165.3 b	93 b	76.7 a	12.2 b
2016–2017	74.5 a	198.1 a	109 a	69.3 b	13.1 a
T x S	ns	ns	ns	ns	*

Note: ED: equatorial diameter; TSS: total soluble solids; ANOVA: T×S interaction; ns: not significant. Means followed by different lowercase letters in columns indicate significant differences according to the Tukey test (P ≤ 0.05).

[*] $p \leq 0.05$.

[**] $p \leq 0.01$.

The total soluble solids showed a higher concentration of sugars in the fruit grown during the second season for both soils. Considering that the minimum acceptable value is 10.5°Brix (FAO, 2010), all treatments would comply with this requirement (Tables 2 and 3). However, Yuri et al. (2019) mention that 12°Brix is required to export from Chile; in such case, T2 and T3 treatments in clay-loam soil (Table 2) and T1 treatment in stony loam soil (Table 3) did not reach this minimum value in the first season.

3.5. Analysis of number of laterals per row: costs and production

Based on the results herein and from an economic point of view, the annual equivalent marginal income gained by investing in two additional drip laterals per row (T3) at Santa Mercedes farm (annual interest rate of 8%) is profitable. Considering that drip tubing costs approximately US$ 0.20/m, and fruit prices average US$ 0.3/kg (ODEPA, 2020), the investment required for adding two extra laterals per row would be paid in one year, even at a marginal increase of annual fruit production near 4.0 t ha^{-1}, with all other variables constant. Thus, the observed increase in yield in one year (8.0 t ha^{-1}) would pay twice for the investment necessary to irrigate with four laterals (T3) apples in Santa Mercedes farm. Another option to be explored in low soil water storage situations is to use micro-sprinklers that would wet a larger surface area instead of drippers. This would be strictly an engineering and economic decision. By contrast, at the El Manzano farm, given our experimental results, the expected increase in marginal revenue by reducing the standard two-laterals per tree row installation to one lateral per row does not make economic sense. However, for new projects in this type of soil one lateral per row reduces the initial costs of the irrigation system in the first years of the orchard.

4. Conclusions

This study shows that variations in the wetting patterns under drip irrigation caused significant differences in fruit yield and quality on two different soil types in the production of Gala Brookfield apple orchards, grafted on M.9 dwarf rootstock. The best results varied with soil type, emphasizing the need to consider availability of stored soil water in drip irrigation design. In the clay-loam soil yields were higher with a one lateral per row and two $4\,\mathrm{L\,h^{-1}}$ emitters per tree (T1: $59.29\,\mathrm{t\,ha^{-1}}$) while, in a stony loam soil, the highest production was obtained with four laterals per row and eight $1\,\mathrm{L\,h^{-1}}$ emitters per tree (T3: $50.82\,\mathrm{t\,ha^{-1}}$), pooled over the two growing seasons. The research showed that there was a positive response to increasing the number of emitters in Santa Mercedes farm, beyond the normal two drip lines that farmers use, due to its stony loam soil type.

Soil water monitoring confirmed that the different irrigation treatments induced different soil wetted volumes and extraction patterns. In the-clay loam soil, T1 provided the most adequate wet volume for deeper extraction. However, in the stony loam soil with four laterals per row (T3) and daily irrigation frequency, the volume of soil wetted in the first 45 cm of soil depth in T3 was greater than in the other two treatments.

Applied water in the clay-loam soil was similar to the estimated volume by AQUASAT in both seasons. By contrast, in the stony loam soil, especially for the second season, there was an irrigation deficit relative to that estimated by AQUASAT. This may explain the greater fruit production in the farm with clay-loam soil in both seasons, but emphasizes the need to wet an adequate soil volume under deficit irrigation as well.

Based on the results obtained in mature Gala Brookfield apple trees, grafted on M.9 dwarf rootstock, it was established that the treatment of one lateral per row with two $4.0\,\mathrm{L\,h^{-1}}$ emitters per tree and irrigated three times a week would be appropriate for clay-loam soil, while four laterals per row with eight $1.0\,\mathrm{L\,h^{-1}}$ emitters per tree and daily irrigation would be most suitable for the stony loam soil and other similar soils of low storage capacity.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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Corrigendum

Corrigendum to “Effects of the number of drip laterals on yield and quality of apples grown in two soil types” [Agric. Water Manag. 248 (2021) 106781]

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The authors regret to ask a corrigendum on the affiliation of D. Rivera. The corrected one is: “[e]Universidad del Desarrollo, Facultad de Ingeniería, CiSGER, Las Condes, Chile’’.

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