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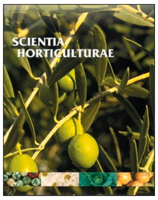

Effect of different irrigation systems on water use partitioning and plant water relations of apple trees growing on deep sandy soils in the *Mediterranean climatic conditions, South Africa*

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ABSTRACT

All commercial apple fruit (*Malus Domestica* (Borkh) exported from semi-arid regions are grown under irrigation with drip and micro sprinkler systems being the most widely used. Few studies have directly compared the physiological responses of fruit trees to these systems in detail leading to uncertainties around their performance. This study investigated variations in transpiration rates, tree water status, growth, water use partitioning, fruit yield and quality for trees growing on deep sandy soils under these two systems. Data were collected in a mature Royal Gala orchard in South Africa over three growing seasons. Tree transpiration was quantified using the heat ratio method of monitoring sap flow while the soil water balance approach was used to derive the evapotranspiration (ET) rates. Leaf level results showed that one day after irrigation on hot dry days, the stomatal conductance was, on average, almost double for trees under micro than those under drip irrigation. There was more stress under drip with the minimum midday leaf water potential dropping to under -1.80 MPa compared to only around -1.20 MPa under micro sprinklers. Consequently, the tree transpiration per unit leaf area was substantially higher under micro sprinkler (2.9 $L/m^2/d$) compared to 2.3 $L/m^2/d$ under drip ($P \leq 0.05$). Canopy growth was slower under drip with peak leaf area index (LAI) around 2.1 compared to 2.7 under the micro sprinkler system. The micro sprinkler system had a more active ground cover than the drip. At peak canopy cover in summer, up to 28% of ET was derived from the orchard floor under micro compared to only 15% under drip. However, fruit size and fruit quality were lower under drip compared to micro sprinkler irrigated trees. The study highlights that while water savings are high under drip irrigated orchards on sandy soils, trees tend to experience considerable water stress culminating in smaller fruit of compromised quality.

1. Introduction

Irrigated agriculture consumes more than 60% of the world's freshwater resources (Reinders et al., 2013; Reddick and Kruger, 2019). However, water for irrigation is increasingly becoming limited, especially in key fruit producing countries in the Mediterranean regions such as South Africa, Italy, and Spain, amongst others (Stevens and van Koppen, 2015; Hortgro, 2021). This is mainly due to climate variability and change that is increasing the frequency and severity of droughts, rising competition for water between agriculture, industry, recreation, and growing populations (Dzikiti et al., 2018). In South Africa, for example, all commercial fruit produced for export are grown under irrigation (Volschenk et al., 2003; Gush et al., 2019; Mobe et al., 2021). Yet the available water resources are almost fully allocated in the major fruit growing catchments (Hope et al., 2008). This means that future expansion of the fruit industry can only be achieved by increasing water use efficiencies using the existing water allocations (Reinders et al., 2013; Dzikiti et al., 2018).

The need to reduce water consumption, while producing high yields of good quality fruit, has seen the widespread adoption of water saving irrigation technologies such as drip and micro sprinkler systems in orchards (Fereres and Soriano, 2007; Gush and Taylor, 2014). However, proper design and implementation of these methods requires a good understanding of the soil-plant-atmosphere interactions for optimal operation and to improve water use efficiency (Kadigi et al., 2019). Lack of detailed information on tree physiological responses to these systems

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has caused uncertainties on the best irrigation methods in water scarce countries like South Africa. This has resulted in farmers switching from one irrigation system to another on a trial-and-error basis, without good scientific evidence. For example, micro sprinkler irrigation wets larger soil surface areas than drip (Simoes et al., 2020). This inevitably affects the development and distribution of root systems which may ultimately affect tree water and nutrient uptake rates (Taiz et al., 2015; Dzikiti et al., 2022). While some studies exist comparing the irrigation volumes applied under drip and micro sprinkler systems (Fallahi et al., 2010), no comprehensive measurements exist directly comparing the tree transpiration dynamics due to these two irrigation practices. Insufficient water supply to the root zone causes stomatal closure, which reduces both transpiration and photosynthesis and overall orchard productivity (Fernández et al., 2020). Drip irrigation, on the other hand, is known to reduce field floor evaporation (Rao et al., 2017). But few studies have directly measured and compared the orchard floor evaporative fluxes

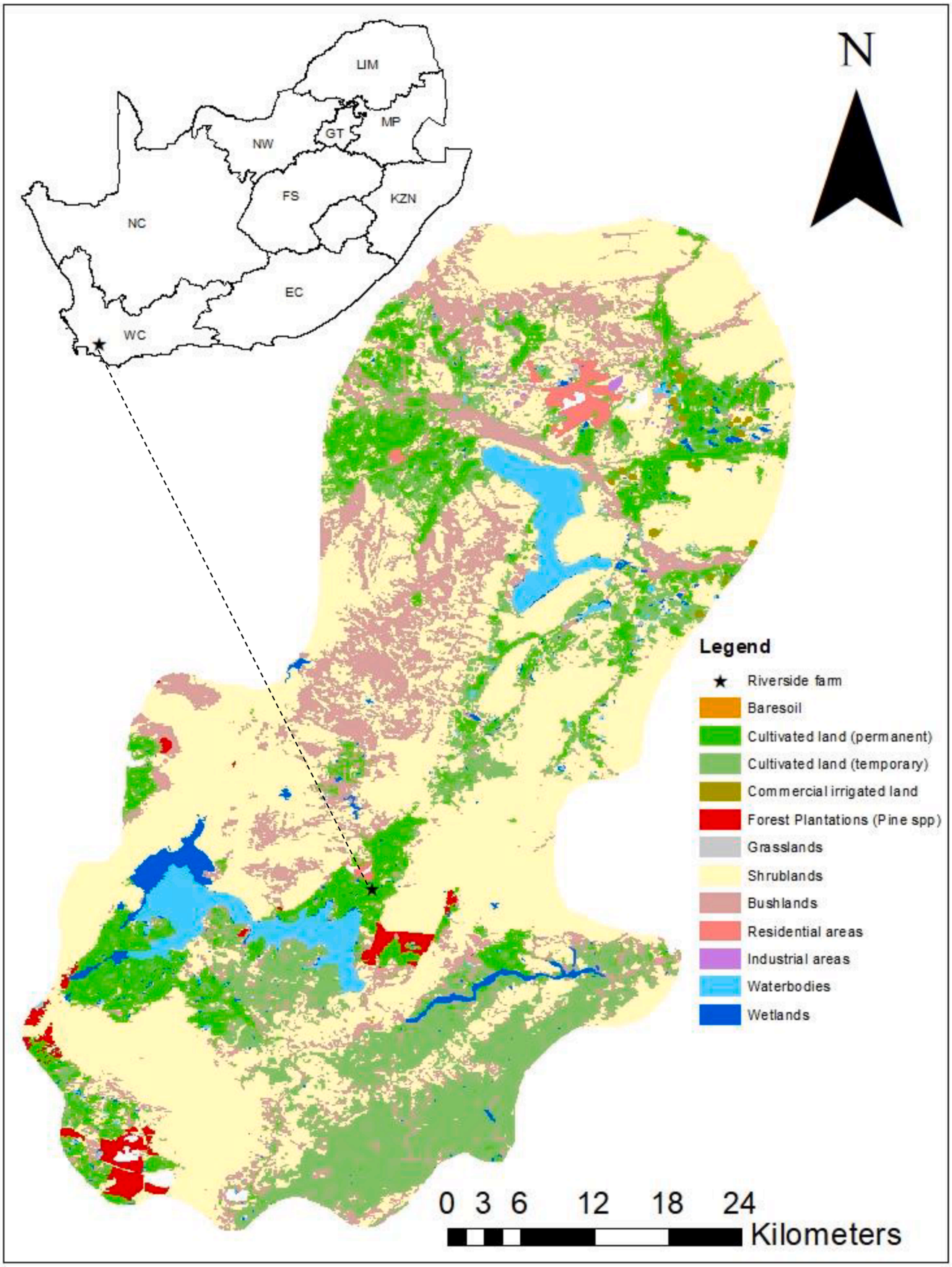

Fig. 1. Location of the study site in the Western Cape (WC) Province of South Africa, showing land use activities in the vicinity, extracted from the national landcover record.

under drip and micro sprinkler systems in commercial orchards under semi-arid Mediterranean conditions. Little is also known about the contribution of the undergrowth vegetation cover, which is sustained to various degrees by different irrigation systems, on the orchard evapotranspiration dynamics (Ntshidi et al., 2021a). Most studies that have compared the performance of drip vs micro sprinkler irrigation in orchards have focused on the effects on shoot and fruit growth, fruit yield and quality (Fallahi et al., 2010; Chen et al., 2018). Detailed information linking evapotranspiration partitioning to tree water relations and yield is essential for the design of irrigation systems, and for developing accurate irrigation schedules (Kool et al., 2014; Fernández et al., 2020). The objectives of this study were therefore: (1) to measure and compare the transpiration dynamics of apple trees growing under drip and micro sprinkler irrigation systems on deep sandy soils in a semi-arid environment, (2) to quantify the effects of the different irrigation systems on evapotranspiration partitioning taking into account the contribution of the understorey vegetation, and; (3) to quantify the effects of the two irrigation systems on tree water status, tree and fruit growth, yield quality and quantity.

Detailed knowledge on crop water use is important to improve water use efficiency (Kadigi et al., 2019) and this is affected by irrigation system, amongst other factors. Water use in orchards is often estimated from readily available weather data using the reference evapotranspiration data calculated using the modified Penman-Monteith equation (Allen et al., 1998). The reference evapotranspiration data are adjusted with appropriate crop coefficients (Mobe et al., 2020a) which are different for different irrigation systems. The information produced in this study will provide insights on how water resources can be best managed in high-density apple orchards growing on sandy soils in the semi-arid Mediterranean regions.

2. Materials and methods

2.1. Study site description

This study was conducted over three years (2017/18, 2018/19 and 2019/20) at Riverside farm (33°57′5″ S; 019°18′44″ E; 317 m asl). The orchard is located about 2.0 km south of Villiersdorp town close to the eastern edge of the Theewaterskloof dam in the Western Cape Province in South Africa (Fig. 1). The study orchard was about 2.36 ha planted to the Royal Gala cultivar on the MM106 rootstock. The orchard was planted in 1998 and the trees were trained with a V-trellis system in north-south orientated rows. Tree spacing between and within the rows was 3 x 2 m giving a tree density of ~1 667 trees per ha. Average tree height was maintained at about 3.5 m.

This orchard was under drip irrigation with pressure compensated drippers delivering about 2.3 L h^{-1}. For this experiment 20 trees were selected in one row in the middle of the orchard during the 2017/18 season and their irrigation was converted to a wide range micro sprinkler system with a wetted radius of about 1.2 m.

The rest of the orchard remained under drip irrigation. The drip lines were on the soil surface with emitters spaced at 0.70 m along the drip line and each tree row had one drip line. The micro sprinkler irrigated trees had one micro sprinkler per tree, each delivering 30 L h^{-1}. The micro sprinkler irrigation was schedule separately from the drip. Irrigation scheduling for the drip was done by the farmer using both soil water content measurements and weather data. The volumetric soil water content in the root zone was measured using profile capacitance probes (Model: Dirk Friedhelm Mecker (DFM), South Africa) at several depths in the range 10 to 100 cm. Weather data were used to determine the crop water requirements calculated as the product of a crop coefficient (Kc) and the reference evapotranspiration (ETo) according to Allen et al. (1998). The farm used a crop coefficient of 1.0 based on published information for mature apple orchards (Allen et al., 1998). Irrigation for the micro sprinkler system was applied every second or third day while that under drip was almost daily depending on weather conditions. There was an active understorey vegetation (cover crop) of the tall fescue variety (*Festuca arundinacea*) that mostly grew on the wetted areas, spanning over ~0.5 m in the middle of the tree rows for the micro sprinkler irrigated trees. The rest of the inter-row spaces for the drip irrigated sections were bare except for vegetation that grew along the drip lines.

The orchard was on flat terrain, and it had no ridges. The soils were loamy sandy soils of the Fernwood soil form (Hyperalbic Arenosol, Soil Classification Working Group,1991) with a low stone content and pH of ~6.5. The physical and chemical properties of the soil are summarized in Table 1, the soil samples were taken from four levels down the soil profile.

2.2. Data collection

2.2.1. Site microclimate, soil water content, and irrigation measurements

The microclimate of the study site was measured using an automatic weather station located about 150 m from the edge of the orchard. The station measured solar radiation, air temperature, relative humidity, wind speed and direction. Reference evapotranspiration (ETo) was calculated following the FAO-56 Penman Monteith approach (Allen et al., 1998). The automatic weather station was installed over a uniform short grass surface whose attributes resemble the grass reference crop (Allen et al., 1998). Equipment used comprised a pyranometer (Model: SP 212 Apogee Instruments, Inc., Logan UT, USA) that measured the solar irradiance. Air temperature and relative humidity were measured with a temperature and humidity probe (Model: HMP60 Campbell Scientific, Inc., Logan UT, USA) installed at ~2.0 m above the ground. A three-cup anemometer and wind vane (Model R. M. Young Wind Sentry Set model 03,001, Campbell Scientific, Inc., Logan UT, USA) measured wind speed and direction, respectively at 2.0 m height, while rainfall was recorded using a tipping bucket rain gauge (Model: TE525-L; Campbell Scientific, Inc., Logan UT, USA). All the sensors were connected to a data logger (Model: CR1000 Campbell Scientific, Inc., Logan UT, USA) programmed with a scan interval of 10 s. The output signals were processed at hourly and daily intervals.

In order to compare the soil moisture regimes in the rootzone of the two treatments, additional data on the volumetric soil water content was monitored at various depths using time domain reflectometer probes (Model: CS616, Campbell Scientific, USA). The sensors were installed at 0.25, 0.50 and 1.0 m from the soil surface, for each irrigation system which covered the effective root zone that extended to about 0.7 m. The actual volumes of irrigation applied were measured using electronic water flow meters (Model ARAD: Multijet, Netafim™, South Africa) that were installed along the irrigation lines.

2.2.2. Tree transpiration and water status measurements

Tree transpiration was measured using the Heat Ratio Method (HRM) of the heat pulse velocity sap flow monitoring technique (Burgess et al., 2001). Three trees with varying stem sizes were selected and instrumented in each treatment. The sap flow sensors were installed about 10–15 cm above the scion-rootstock bud union. The sap flow rates were measured at hourly intervals throughout the study period. The HRM equipment comprised of a heater inserted in the xylem midway (~ 5 mm) between an upper and lower T-type thermocouple (TC). Four TCs were installed in each tree at different depths in the sapwood to account for the radial variations in sap velocity (Wullschleger and King, 2000). Drilling of the holes was performed with a battery-operated drilling machine, using a drill template strapped to the tree, to ensure that the holes were vertically aligned with the axis of the stem (Ntshidi et al., 2018b). The duration of the heat pulse was about 10 s, and this was initiated via the control ports on the CR1000 data loggers (Campbell Scientific, Logan, UT). An AM16/32B multiplexer (Campbell Scientific, Logan, UT) was used to expand the number of channels to measure the sapwood temperature.

The heat pulse velocities, calculated according to Burgess et al.

Table 1
Physical and chemical properties of the soil at Riverside farm in Villiersdorp, Western Cape, South Africa.

	PHYSICAL PROPERTIES										
Depth (cm)	Clay (%)	Silt (%)	Sand (%)	Fine sand (%)	Medium sand (%)	Coarse sand (%)	Stone (%)	Classification	Water holding capacity 10 kPa (%)	100 kPa (%)	mm/m
0–10	6.2	6	87.8	53.4	25.4	9	1.4	Loamy fine sand	22.21	10.34	118.64
25	8.2	8	83.8	48.3	27	8.5	1.36	Loamy sand	22.52	11.3	112.22
50	8.2	6	85.8	51	25.4	9.4	1.45	Loamy fine sand	22.42	10.89	115.35
100	8.2	6	85.8	53.6	28.2	4	1.19	Loamy fine sand	21.97	10.31	116.58
CHEMICAL PROPERTIES											
									Ex. Cations (cmol (+) /kg)		
	pH (KCL)	P (mg/kg)	K (mg/kg)	Cu (mg/kg)	Zn (mg/kg)	Mn (mg/kg)	B (mg/kg)	Fe (mg/kg)	Na	K	Ca
0–10	6.50	152.00	89.20	6.10	7.60	31.00	0.66	65.30	0.95	3.61	83.73
25	6.30	106.00	84.70	5.20	2.40	14.60	0.34	63.90	1.11	4.82	82.04
50	6.50	109.00	79.80	6.60	1.10	10.20	0.30	66.60	1.09	4.47	82.97
100	6.10	40.10	30.60	1.70	4.00	6.80	0.29	57.80	2.39	2.34	77.61

(2001) were corrected for wounding caused by the drilling, using wound correction coefficients described by Swanson and Whitfield (1981). The corrected heat pulse velocities were then converted to sap flux densities according to the method presented by Marshall (1958). The data was also corrected for the density and moisture fraction of the wood according to the procedure by Burgess et al. (2001). Lastly, the sap flux densities were converted to whole-tree total sap flow volumes by calculating the sum of the products of the sap flux density and sapwood area represented by each pair of temperature probes as described by Dzikiti et al. (2018). Individual-tree sap flow volumes (L h^{-1}) were converted to daily totals which were then scaled up to a hectare, in equivalent water depth units (i.e., mm d^{-1}), using the sapwood area index of the orchard as detailed in Dzikiti et al. (2018).

To establish quantitative relationships between the tree water status and the extent of stomatal opening under the different irrigation systems, the leaf water potential was measured concurrently with the stomatal conductance. The leaf water potential was measured using a Scholander-type pressure chamber (Model: 615 PMS Instrument Company, Albany, OR, USA) while the stomatal conductance was measured using a diffusion porometer (Model AP4: Delta-T Devices, Cambridge, UK). These data were collected from four healthy and fully expanded leaves on each of three tagged trees per treatment at hourly intervals from sunrise to sunset on selected days. The measurements typically spanned over several wetting and drying cycles. For example, if the trees were watered on Monday, these data would be collected from sunrise to sunset over several days until after the second irrigation event.

2.2.3. Soil evaporation and understorey vegetation transpiration

Soil evaporation was measured using four micro-lysimeters per treatment over the same periods as the plant water status measurements described in the previous section. The micro-lysimeters were installed at different locations on the orchard floor representing different wetting regimes. Changes in the mass of the micro-lysimeters were monitored at hourly intervals using a precision mass balance with a resolution of 0.01 g from sunrise to sun set on selected measurement days. The soil used in the micro-lysimeters was replaced after every 12 h for consecutive measurement days. The whole surface soil evaporation was calculated as the weighted sum of the micro-lysimeter measurements with the area represented by each micro-lysimeter on the orchard floor used as the weights according to the approach by Testi et al. (2004).

Cover crop transpiration was measured using Dynagage stem heat balance sap flow gauges (Model: SGA3, Dynamax Inc., Houston, USA). The sensors were installed on straight stems of the grass and shielded from exogenous heating using shiny reflective aluminium foils according to the manufacturers' recommendations (Van Bavel and Van Bavel 1990). The cover crop transpiration was also measured at hourly intervals with the sensors connected to a CR1000 datalogger. The sap flow sensors were installed on three to four understorey plants per treatment over a few days.

2.2.4. Tree and cover crop leaf area index measurements

The orchard leaf area index (LAI) for the trees under the different irrigation systems was measured monthly throughout the growing season using an LAI- 2000 Plant Canopy Analyser (LI-COR Inc., Lincoln, NE, USA). The data were taken on overcast days when the assumption that leaves behaved like black bodies was most realistic. The leaf area index of the cover crop (LAI_c) was measured destructively by cutting all the plants in five randomly selected 50 x 50 cm quadrants on the orchard floor and measuring their actual leaf area using the leaf area metre (Model Li-3000, Li-COR Inc., Nebraska, USA). The understorey leaf area index was calculated as the one-sided leaf area per quadrant divided by 2500 (50 x 50 cm) and an average value determined. At the end of the measurement cycle, all the single cover crop plants instrumented with stem heat balance sap flow sensors were cut and the actual leaf area (LA) of the individual plants measured (Ntshidi et al. (2021b).

Cover crop transpiration, in mm d^{-1}, was calculated as the product of the average sap flow normalized with the transpiring leaf area and multiplied by the leaf area index of the cover crop as described by Ntshidi et al. (2021a). Whole surface evapotranspiration under each treatment was estimated using the universal soil water balance approach described in the FAO 56 (Allen et al., 1998).

2.3. Fruit yield and quality

To determine fruit quality under drip and micro sprinkler irrigation systems, the study trees were strip harvested at the end of the growing season. The number of fruit and total mass of fruit per tree were recorded from 10 randomly selected trees per irrigation type. Their average fresh mass of individual fruit was determined using a precision mass balance (Model SNUG III Jadever; Taiwan, China) measuring to the nearest 0.1 g. This information was subsequently used to estimate the total fruit yield per tree as the product of the average mass and the fruit number. A subsample of 20 randomly selected fruit from each treatment were chosen and taken to the laboratory for quality assessment. Fruit quality variables analysed were: (1) fruit firmness, (2) fruit diameter, (3) fruit mass, (4) background colour, (5) starch, and (6) Total Soluble

Solids (Lado et al., 2014). Fruit firmness was measured using a penetrometer while fruit diameter was measured using a pair of vernier callipers. Background colour was determined using the UNIFRUCO colour chart for apples (Steyn, 2020) in which a score of 0.5 represented green fruit and 5.0 yellow fruit. Starch breakdown at harvest was determined using an iodine solution and scored according to the UNIFRUCO starch conversion chart (Steyn, 2020). A digital refractometer (Model PR 32-α, Atago Co., Ltd., Tokyo, Japan) was used to determine total soluble solids (TSS) concentration of fruit at harvest.

2.4. Statistical analyses

Data collected from the trial was subjected to analysis of variance (ANOVA) using STATISTIX 10.0 (Tallahasse, USA). Mean separation tests were done using Tukey HSD at ($\alpha \leq 0.05$) for mean comparison (Gomez and Gomez, 1984). Statistical analysis was performed on the differences in tree water status, water use, fruit yield and quality.

3. Results

3.1. Microclimate

A summary of the climatic conditions during the three growing seasons (2017/18, 2018/19. 2019/20) are shown in Table 2. The highest temperatures recorded for the summer months (Nov–Mar) over the three growing seasons reached 38 °C while in winter (May- Jul) the lowest recorded temperature was 0.8 °C. The vapour pressure deficit (VPD) of the air peaked at 2.8 kPa in summer and dropped to ~0.1 kPa in winter. Annual rainfall during the 2017/18 growing season (Oct–May), was ~316 mm while in 2018/19 rainfall was slightly less (~ 226 mm). In the 2019/20 growing season, the amount of rainfall recorded was about 338 mm. The seasonal total reference evapotranspiration (ETo) calculated following the modified Penman-Monteith equation for a short grass reference was about 1 018, 964, 928 mm in the 2017/18, 2018/19, and 2019/20 growing seasons, respectively. In all three seasons the ETo was three to four times higher than the rainfall.

3.2. Plant water use and its drivers

Micro sprinkler irrigated trees had a higher peak summer LAI of about 2.7 ± 0.2 compared to approx. 2.1 ± 0.2 for the drip irrigated trees (Fig. 2). The effect of reference evapotranspiration (ETo) on tree transpiration from trees under both irrigation systems is shown in Fig. 3.

At the leaf level, transpiration per unit leaf area was higher under micro sprinkler at 2.9 L m^{-2} d^{-1} compared to 2.3 L m^{-2} d^{-1} under drip. As expected, the diurnal trends in tree transpiration from both irrigation

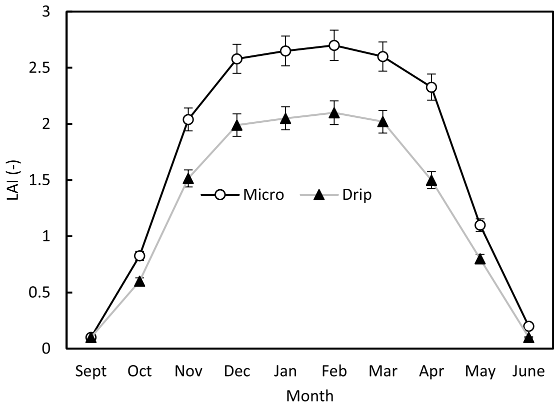

Fig. 2. Seasonal changes in the tree leaf area index (LAI) of the Royal gala trees under different irrigation systems.

Table 2

Summary of the microclimate at the study site over three fruit growing seasons from October 2017 to May 2020. Tmax is the maximum air temperature; Tmin is the minimum air temperature, RHx is the maximum relative humidity, RHn is the minimum relative humidity, Rs is the daily total solar radiation, U_2 is the windspeed at 2.0 m height, ETo is the reference evapotranspiration, and VPD is the vapour pressure deficit of the air.

2017/18 growing season									
Date	Tmax	Tmin	RHx	RHn	Rs	U_2	Rain	ETo	VPD
	°C	°C	%	%	MJ/m^2/d	m/s	mm	mm	kPa
Oct	21.48	6.97	90.99	32.70	23.55	1.54	49.51	125.09	0.76
Nov	23.94	9.63	91.41	34.81	26.70	1.46	56.13	142.57	0.81
Dec	27.06	11.55	90.28	31.34	29.39	1.39	4.57	172.17	1.04
Jan	28.58	13.78	90.68	36.70	27.93	1.30	31.50	169.95	1.06
Feb	28.83	12.74	93.71	29.74	25.79	1.37	20.32	142.60	1.09
Mar	25.45	11.44	93.41	36.33	19.76	1.28	7.86	115.88	0.80
April	23.72	9.74	91.75	35.15	16.06	1.46	37.08	89.34	0.75
May	20.96	9.26	88.64	37.76	10.59	1.51	109.22	60.68	0.67
Total							316.19	1018.28	
2018/19 growing season									
Oct	25.37	10.51	86.83	30.92	22.35	1.53	33.01	133.47	1.04
Nov	25.10	9.00	92.30	29.57	25.36	1.32	29.46	139.92	0.89
Dec	26.69	11.46	93.70	33.19	26.49	1.19	10.66	156.03	0.91
Jan	27.44	12.16	92.02	32.23	27.38	1.40	16.00	162.79	0.99
Feb	29.21	13.85	92.41	34.52	22.74	1.24	7.61	129.26	1.05
Mar	25.51	12.71	95.07	44.06	17.30	1.05	66.55	102.65	0.67
April	23.61	9.78	93.09	37.77	13.96	1.21	10.92	78.39	0.70
May	21.70	7.73	92.69	35.51	10.28	1.35	51.30	61.88	0.68
Total							225.51	964.39	
2019/20 growing season									
Oct	22.34	8.28	92.52	32.08	21.20	1.27	91.19	114.93	0.70
Nov	24.21	9.68	90.95	35.95	24.63	1.31	7.87	135.09	0.85
Dec	25.86	11.19	88.37	32.91	26.57	1.57	16.77	153.73	0.92
Jan	27.08	13.48	93.56	43.55	23.82	1.18	105.66	143.52	0.83
Feb	28.82	14.16	91.32	37.97	23.50	1.40	3.55	142.03	1.00
Mar	26.83	12.25	93.75	39.65	18.23	1.04	1.78	108.00	0.78
April	23.51	8.74	92.22	36.27	13.90	1.12	44.20	74.86	0.72
May	22.50	7.27	91.45	34.58	10.55	0.96	66.80	55.59	0.69
Total							337.82	927.75	

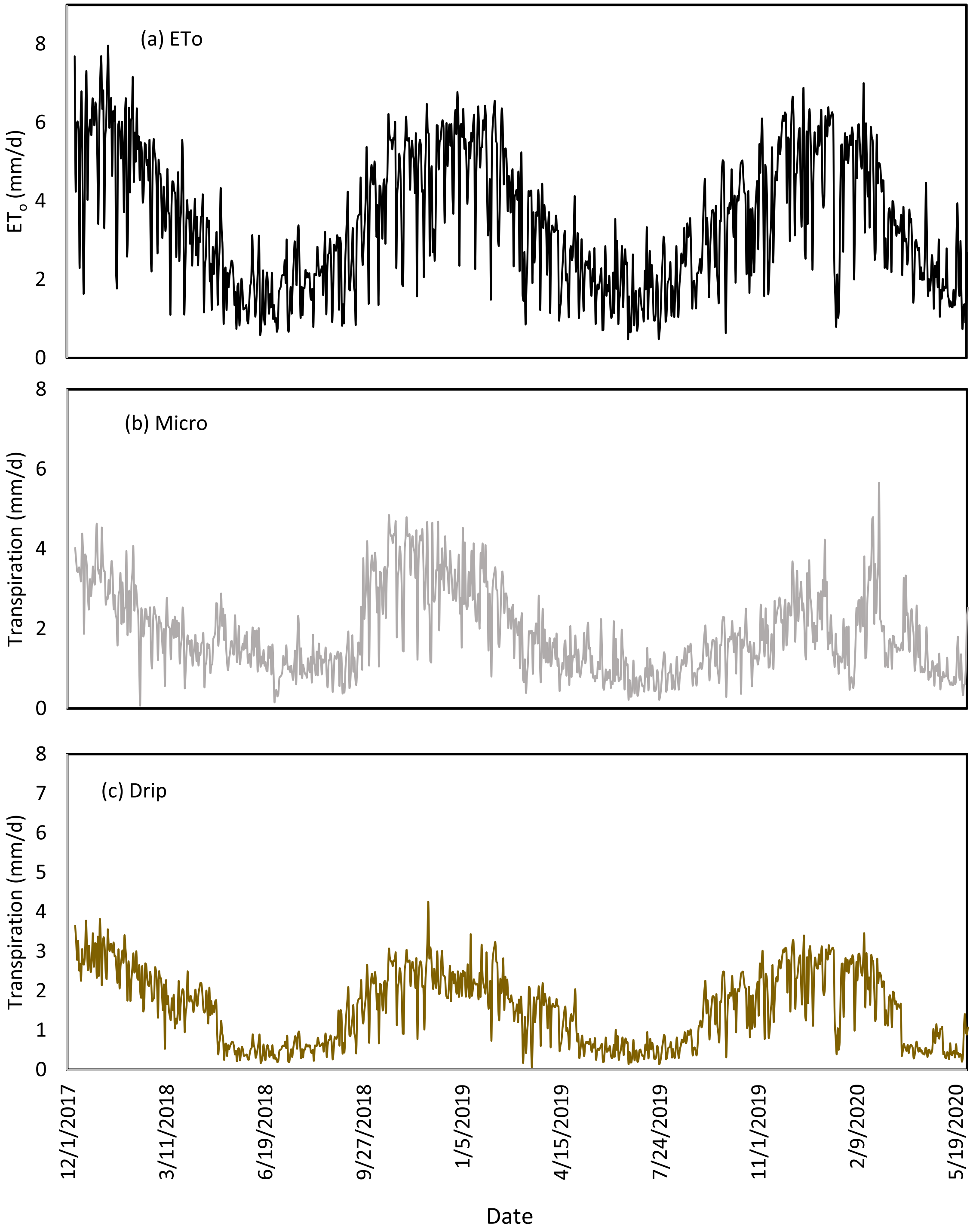

Fig. 3. The seasonal course of (a) reference evapotranspiration (b) Water use of micro-sprinkler irrigated trees (c) Water use of drip irrigated trees at Riverside farm in Villiersdorp over the three apple growing seasons (2017/18, 2018/19 and 2019/20).

systems followed the course of the atmospheric evaporative demand, depicted by the reference evapotranspiration. Maximum transpiration of micro sprinkler irrigated trees scaled up to the whole orchard reached almost 5.6 mm d^{-1} during the hot summer months. These declined to almost zero during the dormant winter months when the trees shed their leaves. The same trends were observed with the drip irrigated trees only that they had a lower transpiration peak at less than 4.3 mm d^{-1} during the same period (Fig. 3). Seasonal transpiration totals (September to June) averaged over the three seasons were lower under drip at approx. 430 mm compared to about 490 mm under micro sprinkler irrigation (Fig. 4). The main environmental variable that drove the water use of the trees grown under micro sprinkler and drip irrigation systems was the solar irradiance, with a coefficient of determination (R^2) of ~0.89 for micro sprinkler and ~0.84 for drip, followed by the ETo with an R^2 of ~0.76 for micro sprinkler and ~0.71 for drip (data not shown). The VPD of the air showed and transpiration had a logarithmic relationship for both irrigation systems with an R^2 of ~0.64 and ~0.65 for micro sprinkler and drip irrigation system, respectively (data not shown).

3.3. Evapotranspiration partitioning and soil water content

Detailed measurements of the partitioning of ET were done over a 4-

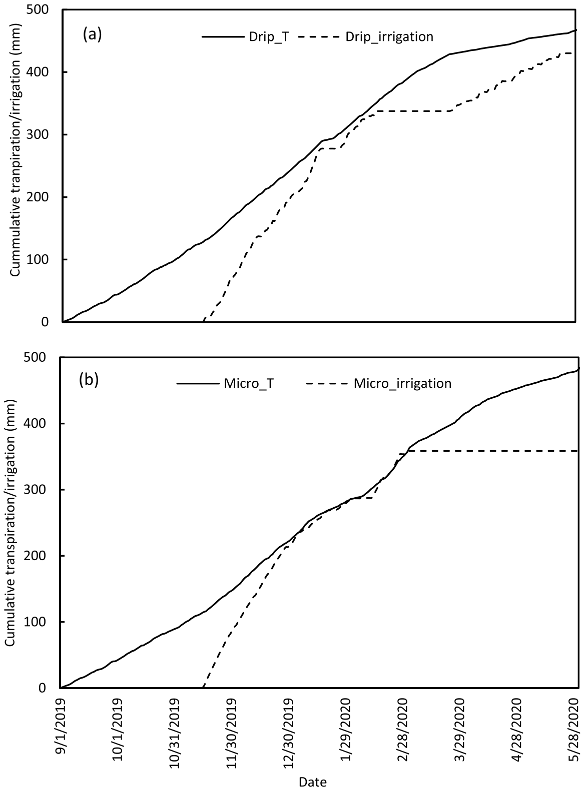

Fig. 4. Cumulative transpiration and irrigation of (a) drip irrigated trees and (b) micro-sprinkler irrigated trees in the 2019/20 growing season.

day period in summer from 22 to 25 January 2019. During this period evapotranspiration (ET), transpiration (T), soil evaporation (Es), and cover crop transpiration (Tc) were all quantified in detail. For the drip irrigated trees, irrigation was applied daily for about 3 h at a time (Fig. 5a). For trees under the micro sprinkler system, irrigation was applied once every two to three days for about 1.5 h at a time. The results from the study show that tree transpiration contributed ~85% of the total ET under drip irrigation, while the second highest contribution was from soil evaporation at ~10% and cover crop transpiration (grass growing in-between trees and not interrow spacing) only contributed ~5% to the total ET. On the micro sprinkler irrigated side of the orchard row, tree transpiration contributed ~72% to the total ET, while the cover crop transpiration was the second largest contributor at ~19%; soil evaporation had the least contribution at ~9%.

Over the three days when irrigation was not applied under micro sprinklers, Fig. 5d shows that there was a decline in all the measured fluxes (transpiration, soil evaporation and cover crop transpiration), showing the dependence of all the fluxes on applied irrigation. For the micro sprinkler irrigated side of the orchard row, the highest soil moisture content recorded was roughly 0.17 cm^3/cm^3 (Fig. 6a), with the highest soil water content recorded by the shallower sensors (Fig. 5c), the deepest sensor was in relatively drier conditions indicating that there was no deep percolation beyond the root zone. For the drip irrigated trees, the highest soil water content recorded was roughly 0.2 cm^3/cm^3 (Fig. 6b), with sensors at all depths recording moisture content of more than 0.19 cm^3/cm^3 (Fig. 5a). There was little fluctuation in soil water content in the deeper sensor at 1.0 m depth. This suggests that the applied water seeped beyond the rootzone in the wetted soil bulb with little to no water uptake at that depth.

3.4. *Tree water relations*

The stomatal conductance of the micro sprinkler irrigated trees ranged from 0.1 ± 0.2 to 0.9 ± 0.2 cm/s while that of the drip irrigated trees ranged from 0.16±0.2 to 0.5 ± 0.2 cm/s (Fig. 7a&b). The stomatal conductance was maximum at mid-day while lower values were recorded in the early morning and late evening. The leaf water potential (LWP) of the well-watered micro sprinkler irrigated trees was higher ranging from -0.4 ± 0.2 to -1.2 ± 0.2 MPa (Fig. 7c) while that of drip irrigated trees ranged from -0.5 ± 0.2 in the morning to -1.8 ± 0.2 MPa at midday when the transpiration pull was strongest (Fig. 7d).

A curvilinear relationship was observed between the diurnal trend in the stomatal conductance (Gs) and tree transpiration for both micro sprinkler and drip irrigation systems (Fig. 8a and b). There was a time lag of at least an hour between stomatal opening (in response to light stimuli) and the commencement of transpiration for trees grown under both irrigation systems (data not shown). There exists a linear relationship between tree transpiration and leaf water potential with the coefficient of determination (R^2) of 0.69 for micro sprinkler and 0.66 for drip irrigated trees (Fig. 9a and b). A curvilinear and stronger relationship was observed between the stomatal conductance and leaf water potential for trees grown under both irrigation systems. The coefficients of determination were ~0. 81 and ~0.74 for micro-irrigated and drip irrigated trees, respectively (Fig. 9c and d).

3.5. *Fruit yield and quality*

The micro sprinkler irrigated trees produced on average 143 fruit per tree with an average fruit weight of 125.6 g for the 2017/2018 season. This translated to an average yield of about 18 kg per tree. Drip irrigated trees, on the other hand, produced an average of 192 fruit per tree which were lighter weighing about 87.2 g per fruit. This resulted in a lower yield of about 16.7 kg per tree, also for the 2017/2018 season, the same trend is seen in the seasons that followed. The drip irrigated trees also produced smaller fruit with an average size of about 60 mm in diameter for all the seasons while the micro sprinkler irrigated trees produced larger fruit with an average size of ~70 mm. The fruit size and soluble sugars of the micro sprinkler irrigated fruit showed an increasing trend over the three-year study period (Table 3) possibly due to the trees adapting to the introduced irrigation system. The quality of the fruit from the drip irrigation system was poor as compared to that t from the micro sprinkler irrigated trees.

4. Discussion

The availability of adequate water for irrigation is one of the major threats to sustainable fruit production in key growing areas in the arid and semi-arid regions (Midgley and Lötze, 2008; Reinders et al., 2013; Reddick and Kruger, 2019). Drip and micro sprinkler systems are the most widely used irrigation methods in fruit orchards (Stevens and van Koppen, 2015). Yet no studies have directly quantified, in detail, the effect of these systems on tree water status, tree and orchard water use, fruit yield and quality over many years under semi-arid conditions. This study aimed to close these important information gaps using detailed measurements of the soil-plant-atmosphere interactions in a commercial apple orchard subjected to the two irrigation systems.

Many studies have demonstrated that the size of the wetted area affects the development of the tree root system (Sokalska et al., 2009; Zegada-Lizarazu and Berliner, 2011; Sakai et al., 2015), and the distribution and type of understorey vegetation that grows between the rows (Dzikiti et al., 2018; Gush and Taylor, 2014; Ntshidi et al., 2021a). These factors affect the rate of water consumption by individual trees and by the entire orchard. Trees under drip irrigation tend to develop a narrow root system that is concentrated in the irrigated zone (Gush and Taylor, 2014) while those under micro sprinklers spread their roots over wider areas. This study demonstrated that trees under a single line drip system grown on sandy soils tend to experience considerable water deficit stress even when irrigation is scheduled optimally. This culminated in comparatively lower tree water status, reduced tree and orchard level transpiration rates, and lower fruit quality. Similar results were

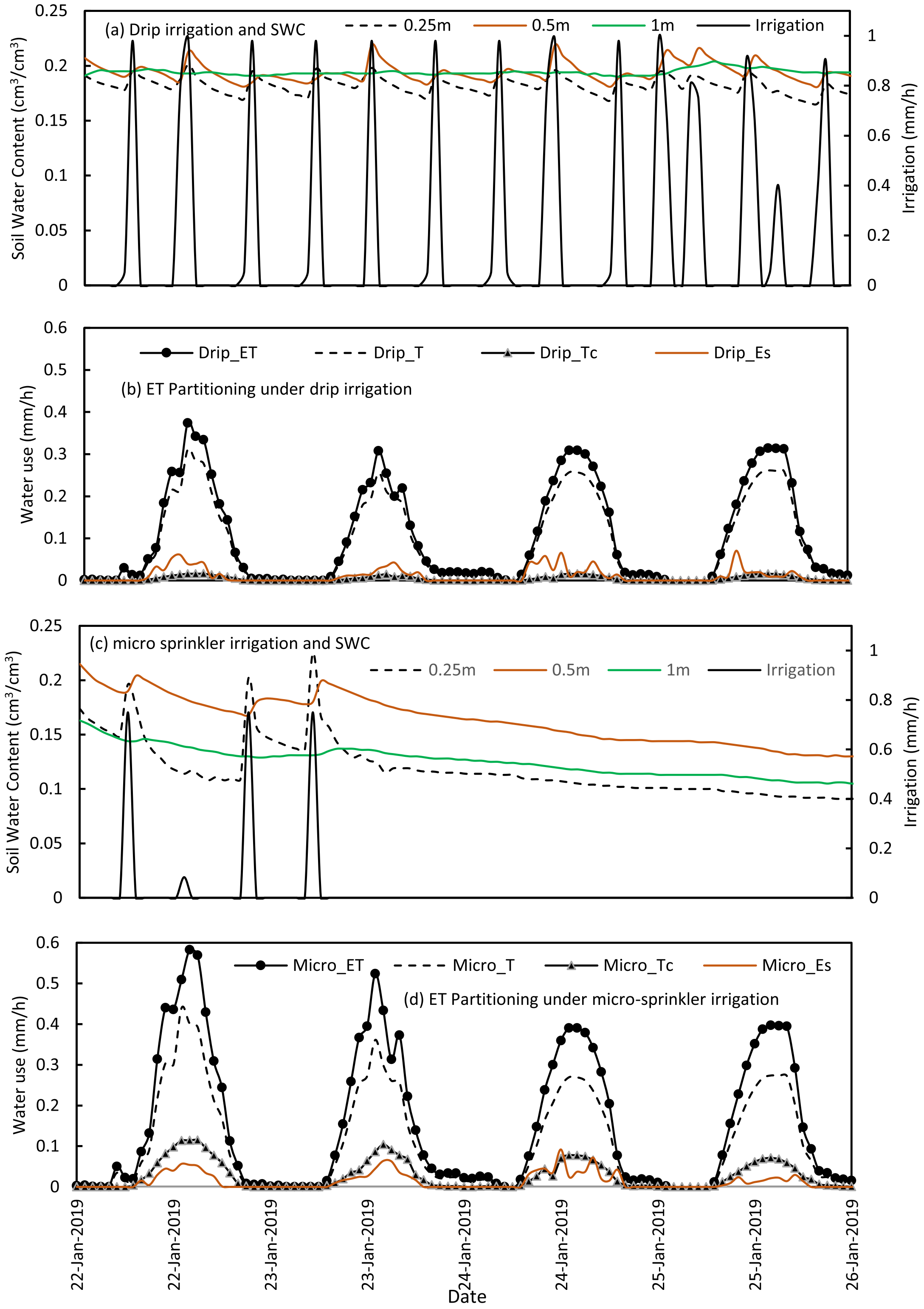

Fig. 5. Soil water conditions and ET partitioning under different irrigation systems (a) Drip irrigation and Soil Water Content, (b)ET partitioning under drip irrigation, (c) Micro-sprinkler irrigation and Soil Water Content and (d) ET partitioning under micro-sprinkler over a wet-dry period.

observed in apple orchards in the USA by Fallahi et al. (2010) who observed that apple trees under drip irrigation received about half of the water applied under micro sprinkler irrigation. However, their trees were subjected to the partial root zone drying and regulated deficit irrigation treatments under both micro sprinkler and drip systems. In the USA study, yield of the trees under drip and subjected to water deficit stress increased in the first year possibly due to a larger number of spurs produced in response to the water stress. But the yield declined in subsequent years compared to the well-watered control treatments. In this study we provide a direct comparison of the drip vs micro sprinkler systems without the deliberate introduction of water stress. The stomatal conductance and leaf water potential were consistently lower

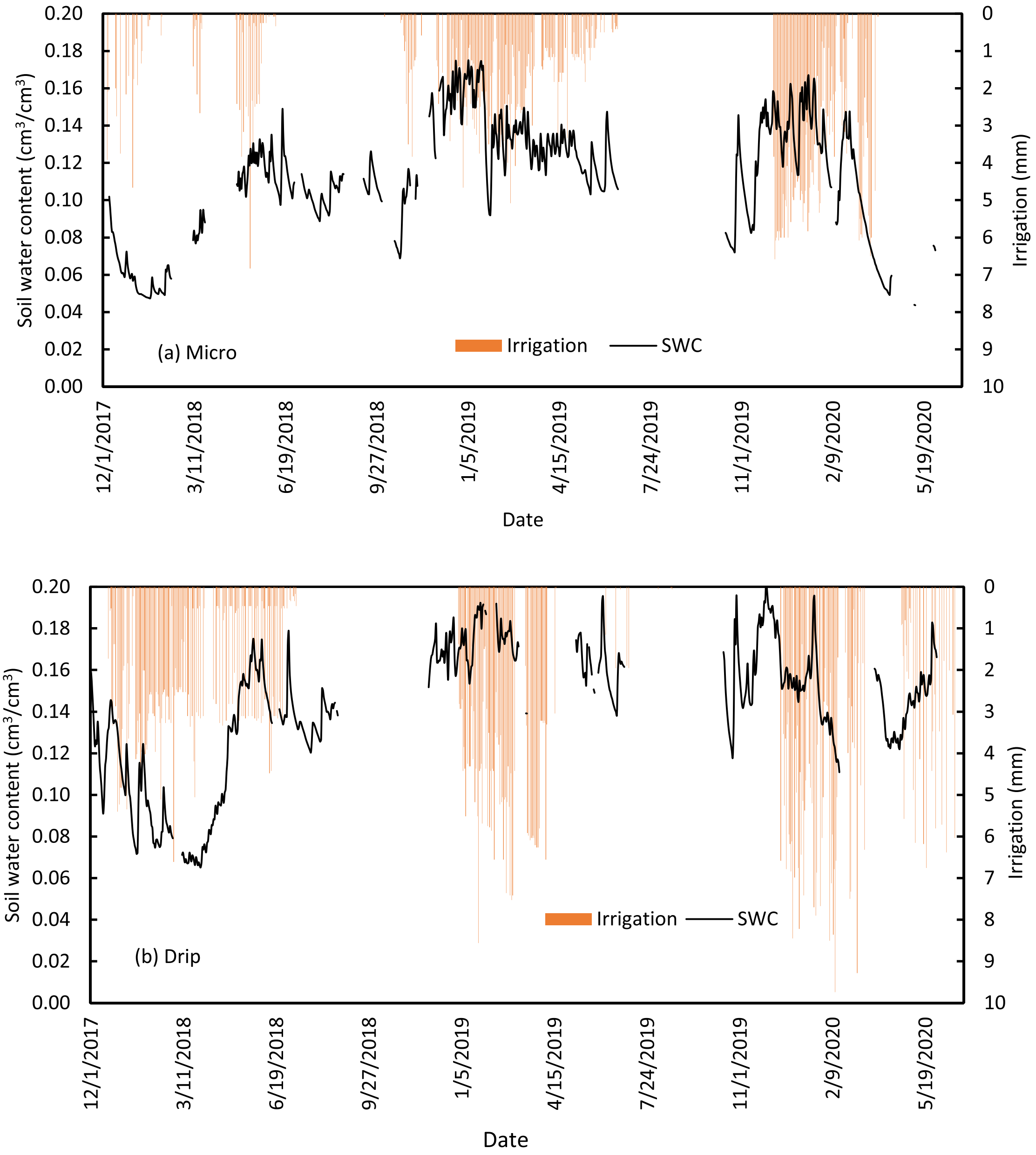

Fig. 6. Average soil water dynamics taken from depths of 25, 50, and 100 cm with applied (a) micro-sprinkler irrigation and (b) drip irrigation over the three seasons.

under drip than micro sprinkler indicating the occurrence of sustained levels of water deficit stress. The order of magnitude of the stomatal conductance measured here are consistent with those observed by Massonnet et al. (2007) when they studied the stomatal regulation of two apple cultivars grafted on the M9 rootstocks in the South of France.

While low orchard water use rates under drip are desirable especially in water scarce production areas as in the Mediterranean regions, it is important that fruit quality is not compromised as this affects the selling price (Dzikiti et al., 2018; Hortgro, 2021). Fruit quality is one complex subject and can be explained from an external or internal point of view (Musacchi and Seera, 2018). Fruit quality can be affected by (1) environmental factors, (2) orchard design, and (3) management practices amongst others. We found that the quality of apple fruit for trees converted from drip to micro sprinkler gradually improved in successive seasons as the root system of the trees adapted to a different, albeit optimal, watering pattern. The fruit size improved gradually under micro sprinkler irrigation, though higher crop load recorded under drip irrigation may have contributed to the smaller fruit size (De Salvador et al., 2006; Dzikiti et al., 2018) harvested from drip irrigated trees. In terms of fruit firmness, the smaller fruit were firmer as they tend to have thicker skin (Mpelasoka et al., 2000). Konarska (2015) also found that smaller fruit tend to be firmer when he studied the fruit quality of blueberry cultivars in Poland. Smaller apples tend to have sugars more concentrated, though they are less juicy compared to bigger apples, however, when it comes to the apples market, the driving factor for fruit purchases is the appearance (Musacchi and Seera, 2018), hence bigger fruit will sell faster. Findings made in this study are somewhat contrary to those reported in other studies in which high yields of good quality fruit have been found for apple orchards under drip (Fallahi et al., 2007; Fallahi, 2012; Jiang and He, 2021). Confounding factors that may have contributed to our observations include: (1) use of a single drip line, (2) on trees growing on sandy soils, (3) in an environment with a very high atmospheric evaporative demand (Ntshidi et al., 2018a; Mobe et al., 2020b). It appears that the rate of water uptake by the trees did not

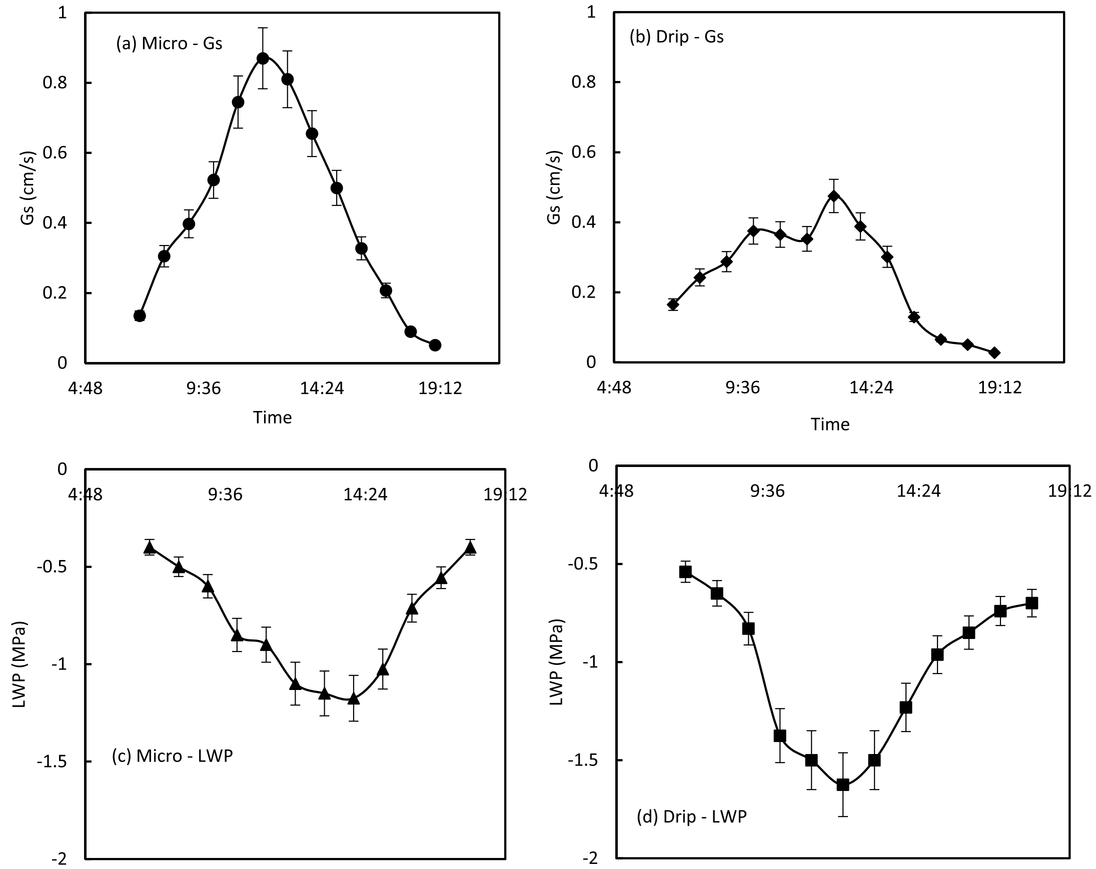

Fig. 7. Typical stomatal conductance of (a) micro-sprinkler irrigated trees, (b) drip irrigated trees; also leaf water potential (LWP) of (c) micro trees and (d) drip trees, over a clear day on 24 January 2019 at Riverside farm. Error bars depict a 10% measurement error for each variable.

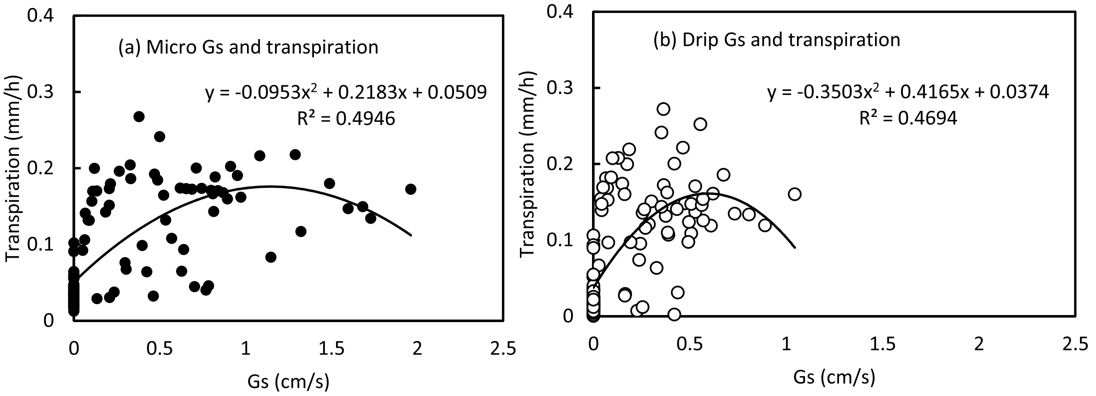

Fig. 8. Relationship between stomatal opening and transpiration of (a) micro-sprinkler irrigated trees and (b) drip irrigated trees.

match the atmospheric evaporative demand given the limited root system due to the smaller wetted area. A lot of the water applied through the drippers seeped through the rootzone resulting in the region beyond the root zone being consistently wet. The micro sprinkler system on the other hand resulted in a more extensive root system and water uptake was sufficient to meet the atmospheric evaporative demand leading to less stress on the trees.

In such situations, introducing a second drip line could have somewhat alleviated the water stress by increasing the wetted surface area. But the water saving benefits of the drip system would diminish. Careful design and implementation of the drip system is therefore critical to achieve optimal yields while minimizing water consumption. While increasing the size of the wetted area using the micro sprinkler system led to higher yield of good quality fruit, non-beneficial water losses through increased orchard floor evaporative fluxes also increased. The dense understorey vegetation consumed larger quantities of water than expected emphasizing the need to carefully select the cover crop type in water scarce production regions. Some cover crop types consume larger quantities of water than others as demonstrated by Ntshidi et al. (2021b).

Despite the issues associated with drip irrigation highlighted in this study, the long-term sustainability of irrigated fruit production in semi-arid environments that are projected to experience drier conditions in future lies with the successful implementation of technologies that use

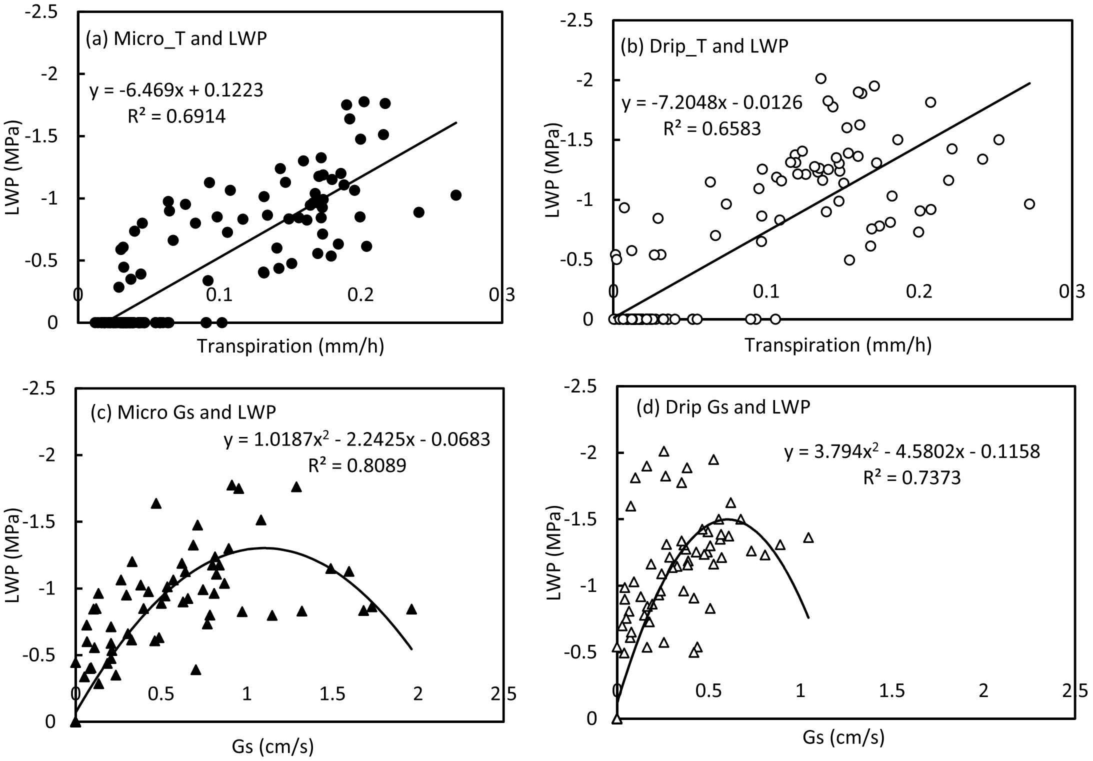

Fig. 9. correlations between (a) transpiration from micro-sprinkler irrigated trees and LWP, (b) drip irrigated trees and LWP, (c) stomatal opening of micro-sprinkler irrigated trees and LWP, lastly (d) stomatal opening of drip irrigated trees and LWP.

Table 3

Summary of the fruit quality attributes for royal gala apple over three fruit growing seasons. Statistical differences are denoted by letters^{a} and^{b}.

2017/18 growing season							
Irrigation system	Firmness (kg)	Diameter (mm)	Mass (g)	Background Colour	Red Colour	Starch	TSS (°Brix)
Drip	8.2^{a}	55.5^{b}	87.2^{b}	4^{a}	8.7^{a}	65.5^{a}	13.5^{a}
Micro	6.72^{b}	57.6^{a}	125.6^{a}	4.02^{a}	8.02^{a}	70.2^{a}	12.15^{b}
Significance	*	*	*	ns	ns	ns	*
2018/19 growing season							
Drip	8^{a}	57.2^{b}	89.4^{b}	4.1^{a}	8.9^{a}	69.5^{a}	13.6^{a}
Micro	6.85^{b}	67.3^{a}	140.35^{a}	4.03^{a}	8.05^{a}	79^{a}	12.19^{b}
Significance	*	*	*	ns	ns	ns	*
2019/20 growing season							
Drip	8.08^{a}	55^{b}	87.2^{b}	4.15^{a}	8.8^{a}	69^{a}	13.4^{a}
Micro	7.18^{b}	68.2^{a}	142.2^{a}	4.05^{a}	8.1^{a}	81.25^{a}	12.54^{b}
Significance	*	*	*	ns	ns	ns	*

Means in the same column, same year, followed by the same letter are not significantly different at $P \leq 0.05$, while means in the same year followed by different letters are significantly different at $P \geq 0.05$. ns = non-significant difference ($P \leq 0.05$), while * = significant difference ($P \geq 0.05$).

less water such as drip irrigation. In countries like South Africa, for example, there is currently widespread conversion of drip irrigated orchards to micro sprinkler (Shaun Spinnler, pers. comm.) partly because of the reasons cited in this study. This trend is quite likely problematic in future as pressure on the limited water resources increases. Further research is therefore necessary to optimize the performance of drip irrigation systems and to reduce problems associated with blockages especially in regions with low quality water. Research into narrower range micro sprinkler systems is also essential to reduce orchard floor evaporative losses which reduces the orchard water productivity.

5. Conclusions

This study confirms the water saving benefits of drip irrigation compared to full surface irrigation systems that have been reported in other studies (e.g., Fallahi et al., 2010). However, we also highlight potential pitfalls and the need for careful design of the drip system to achieve optimal yields using minimum water resources. This study directly quantified the transpiration response of trees under drip and micro sprinkler irrigation in the same orchard and found that: (1) canopy growth was slower for the drip compared to micro sprinkler irrigated trees, (2) fruit quality was inferior under drip than micro sprinkler irrigation due to water stress that reduced photosynthesis rates thereby affecting fruit yield and quality, and; (3) there was more active ground cover under micro sprinkler than under drip leading to larger orchard floor evaporative losses. At peak canopy cover in summer, up to 30% of ET was derived from the orchard floor under micro compared to only 15% under drip. Striking the right balance between achieving optimal yields and saving water requires a detailed understanding of tree response to the specific irrigation system. This will be critical in future as water resources become increasingly scarce under climate change and growing competition between different water users.

CRediT authorship contribution statement

Zanele Ntshidi: Conceptualization, Methodology, Investigation, Formal analysis, Writing – review & editing, Writing – original draft. **Sebinasi Dzikiti:** Investigation, Writing – review & editing, Supervision. **Dominic Mazvimavi:** Writing – review & editing, Supervision. **Nompumelelo Thelma Mobe:** Investigation, Writing – review & editing.

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.

Data availability

Data will be made available on request.

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