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Irrigation optimization enhances water management and tree performance in commercial citrus groves on sandy soil

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Abstract

Citrus production in Florida accounts for nearly 50% of national production in the United States. The goal of this study was to determine the impact of varying irrigation levels on tree growth, leaf nutrient concentrations, and water relations at selected citrus tree densities. During most of the year, significant water distribution and movement were detected across soil horizons as a function of irrigation applied and capillary water rising from the water table. As a result, significant fibrous root length densities (FRLD), median root lifespan, and leaf nutrient concentration were observed in the three-row and two-row experiments with deficit (50%-crop evapotranspiration, (ET_c) and moderate (78%-ET_c) irrigation regimes, respectively. Stomata conductance and stem water potential (y) portray less water stress of the trees when they received moderate irrigation in the low and moderate tree densities than the highest tree density. Moderate irrigation triggered FRLD and improved root survival probability and root lifespan. As a result, irrigation management improved water availability, plant nutrition, and tree growth while efficiently utilizing resources.

Introduction

The growing demand for affordable and healthy food to feed the growing population necessitates multilayered strategies to meet food demand and supply features: excessive irrigation application to overcome the impact of erratic rainfall, which imposes pressure on groundwater withdrawals, adversely affecting crop failure and sustainability (Ferrarezi et al. 2020; Barooah et al. 2023). Concurrent challenges to sustainable agricultural production include rising food demand, global population growth, and the abiotic and biotic stresses in crop production (Vincent et al. 2020; Hamido and Morgan 2021). Agricultural expansion and intensification are expected to meet 70% of the increase in food demands by 2050, exacerbating the negative impacts on water resources (Mbabazi et al. 2017; Holt et al. 2019). Because of increased nitrate concentrations and eutrophication of water resources, nitrogen, and phosphorus leaching is a global water quality challenge (Kiggundu et al. 2012; Cui et al. 2020; Suresh et al. 2023). In South Florida, where annual rainfall is high, sandy soils contribute to nutrient leaching, and reduce crop yield and quality (Sato et al. 2009; Kiggundu et al. 2012; Hamido and Morgan 2020; Ayankojo et al. 2020). As a result, researchers have devised several mechanisms to address the emerging challenges to current irrigation practices, including deficit irrigation (Abrisqueta et al. 2008; Gasque et al. 2016), drip and micro-sprinkler irrigation (Kadyampakeni et al. 2014a; Panigrahi and Srivastava 2017), and irrigation scheduling based on crop water requirement (ET_c) (García Petillo and Castel 2007; Morgan et al. 2010; Hamido and Morgan 2021; Ayankojo and Morgan 2021).

In recent decades, Huanglongbing (HLB, citrus greening) caused tree root densities to decrease in HLB-affected citrus groves (Bodaghi et al. 2022; Reingwirtz et al. 2021). When a citrus tree becomes affected by HLB, approximately half of

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its root density and mass decline before symptoms of HLB become visible on the tree canopy (Bodaghi et al. 2022; Graham et al. 2013; Morgan and Graham 2019). Crop water requirement-based irrigation is lacking on Florida sandy soils for mature HLB-affected citrus trees. Therefore, novel irrigation management practices based on comprehensive crop water demand in response to varying (deficit, moderate, and high) irrigation conditions are urgently required. Several mechanisms have been used by the researchers, including y, stomata conductance (Barkataky et al. 2013; Keel et al. 2007; Mccutchan and Shackel 1992), volumetric soil water content, tree growth (LAI, canopy volume, and fine root length and density) to evaluate varying irrigation methods and quantities (Kiggundu et al. 2012; Hamido and Morgan 2021). Previous findings have also indicated that irrigation management improves tree growth, and fruit yield of fresh tomatoes, citrus, and avocado (Ayankojo and Morgan 2021; Hamido and Morgan 2021; Kadyampakeni et al., 2014c; Kiggundu et al. 2012; Mbabazi et al. 2017).

Understanding seasonal patterns of crop evapotranspiration (ET_c) and crop coefficient estimates (K_c) of a crop are thus the foundations for implementing novel irrigation methods that use real-time weather data (daily minimum and maximum temperature, solar radiation, relative humidity, and wind speed) to develop an irrigation schedule that determines irrigation applied depth and runtime (Mbabazi et al. 2017) for sustainable crop productivity to address the aforementioned global crop production challenges (Mbabazi et al. 2017; Hamido and Morgan 2021; Ayankojo and Morgan 2021; Ippolito et al. 2022). Therefore, the objective of the current study sought to assess fine root length density (FRLD) and root life span, leaf nutrient concentrations, and water relations in response to varying irrigation levels at selected tree densities in commercial citrus groves on Florida sandy soils.

Materials and methods

Study site conditions and treatments

The experiment was carried out on Malabar fine sand (sandy, siliceous, hyperthermic Arenic Alaquods) in a commercial citrus grove near Immokalee, FL, USA (26.35° N, 81.42° W) from 2019 to 2022 growing seasons. Mature thirteen-year-old 'Valencia' (*Citrus sinensis*) citrus trees grafted on Carrizo (a hybrid of Washington Navel orange and *Poncirus trifoliata*) planted in tree densities of 360, 485, and US-897 (*Citrus reticulata* Blanco x *Poncirus trifoliata* (L.) Raf.) citrus rootstock with 920 trees ha^{-1}. The experimental layout consisted of three 300-meter-long beds with two (Fig. 1A) or three (Fig. 1B) rows of trees and drainage swales on each side. The experiment was designed as a split-plot design on three blocks of selected tree densities of 360 and 485 trees ha^{-1}, a micro-jet sprinkler emitter was placed 50 cm away from the tree trunk, and an emitter was placed every two trees in the high (920 tree ha^{-1}) tree density. Three irrigation rates were set with a micro-jet having a different flow rate to meet the projected irrigation ET_c which was determined using the crop coefficient procedure (Morgan et al. 2010; Hamido and Morgan 2021; Ippolito et al. 2022).

The improved irrigation rates were determined using a smart irrigation app for Androids and iPhones developed by the University of Florida and found at Citrus App | Smart-IrrigationApps.org. The daily reference evapotranspiration (ET_o) was calculated using the FAO Penman-Monteith Eq. (1) and the weather data was obtained from the Florida Automated Weather Network (FAWN) station https://fawn.ifas.ufl.edu/.

$$ET_0 = \frac{0.48\Delta(R_n - G) + \gamma\left(\frac{900}{T_a} + 273\right)(U_2)(e_s - e_a)}{\Delta + \gamma(1 + 0.34U_2)} \quad (1)$$
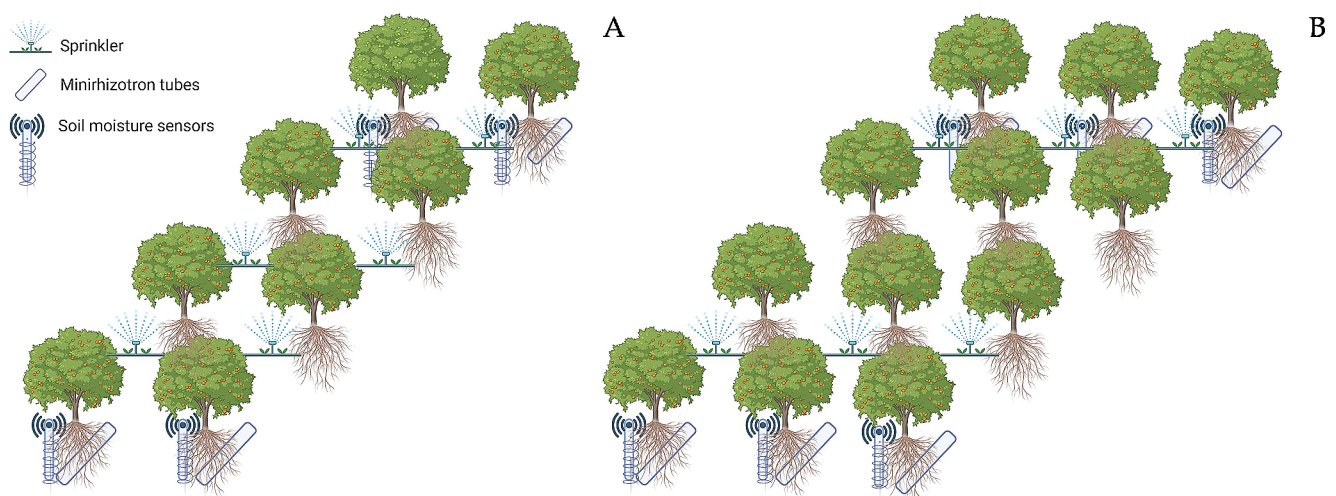

Fig. 1 Field layout of the two-rows (**A**) and three-row (**B**) with the field accessories: sprinkler, minirhizotrons, and soil moisture sensors

Where ET_o is the reference evapotranspiration; Δ [kPa °C^{-1}] is the gradient of the saturation vapor pressure curve, R_n [MJ m^{-2} d^{-1}] is the net radiation at the crop surface, G [MJ m^{-2} d^{-1}] is the soil heat flux density, $(e_s–e_a)$[kPa] is the actual vapor pressure deficit, γ [kPa °C^{-1}] is the psychrometric constant, and U_2 [m s^{-1}] is the wind speed measured at 2 m height from the ground.

According to Allen et al. (1998), ET_c (Eq. 2) can be obtained from a reference evapotranspiration (ET_O) as:

$$ETc = (ET_O) \times (K_C) \times (K_S) \tag{2}$$

where: ET_c = crop evapotranspiration; ET_o = reference evapotranspiration (mm·d^{-1}); K_c = crop coefficient; K_s = soil water depletion coefficient (Morgan et al. 2010). The ratio of ET_c to ET_o is equal to K_c (Eq. 3) in which Ks is assumed to be equal to 1 (Eq. 4) (Morgan et al. 2006; Hamido et al. 2017; Ippolito et al. 2022).

$$Kc = \frac{ETc}{ET_O} \tag{3}$$

$$Ks = \frac{[TAW - (\theta_{FC} - \theta)]}{TAW - RAW} = \frac{\theta - \theta_{WP}}{\theta_t - \theta_{WP}} \tag{4}$$

Where K_s is the soil-water depletion coefficient (≤ 1);TAW is total available water,$\theta_{FC}$is the soil-water content at field capacity; $\theta_{FC} - \theta$ is the readily available soil-water content,θ is soil-water content; RAW is readily available water; θ_{WP} is the soil-water content at the permanent wilting point; andθ_t is the readily available soil-water content.

$$TAW (\%) = \frac{[(WC - FC)]}{(FC - FWP)} \times 100 \tag{5}$$

where TAW is the total and readily available water, WC is the soil water content,FC (10%) is the soil-water content at field capacity, andPWP [1%] is the permanent wilting point (Morgan et al. 2006; Ippolito et al. 2022). The irrigation rates in the current experiment had two different rates for the 360 and 485 trees ha^{-1}(78%-ET$_c$, and 100%-ET$_c$), and the 920 trees ha^{-1} irrigation rates (50%-ET$_c$, 78%-ET$_c$, and 100%-ET$_c$) corresponding to 31.4 L h^{-1}, 48.5 L h^{-1}, and 62.8 L h^{-1} for 50%-ET$_c$ (deficit) 78%-ET$_c$ (moderate), and 100%-ET$_c$ (high /grower standard) emitters, respectively.

Water relations

Soil water content distribution

Eighteen soil moisture probes (SDI-12 Drill and Drop Probe; Sentek, Stepney, South Australia) were used to record the soil moisture pattern at 15, 25, 35, 45, 55, 65, 75, and 85 cm interval depths. Each probe has a capacitance probe located at different points along its 85-cm length allowing for different readings along the soil profile(Morgan et al. 1999; Ayankojo et al. 2020). Each probe was buried vertically into the soil along tree rows, 50 cm away from the tree trunk, and connected to a radio that sends signals and stores data in the cloud every 30 min. The data from the soil probe were calibrated and converted into gravimetric water content (%) of top 0–15 cm soil depth by taking soil samples with a soil core sampler (5 cm × 5 cm) and obtaining soil bulk density simultaneously. Before oven-drying the soil samples, the fresh weight was determined. To calibrate soil moisture determination, an oven-drying gravimetric method was used. The moist soil was dried at 105 °C for 24 h until it reached a constant weight (Schmugge et al. 1980). The gravimetric water soil sample concentration was calculated and expressed as a percentage of dry soil (Eq. 6). Subsequently, the volumetric water content was calculated by multiplying the gravimetric water content by the bulk density (Eq. 7).

$$\theta g = \frac{(m_{wetsoil}) - (m_{drysoil})}{m_{drysoil}} \times 100\% \tag{6}$$

$$\theta v = \frac{(\theta_g)(\rho_{bd})}{(m_{drysoil})\rho_w} \times 100\% \tag{7}$$

where θ_g is the weight of water, m is the weight of the soil, v_g is the volume of soil moisture, and ρ_{bd} is the density of the soil.

Stomatal conductance (g$_s$)

The g_s was measured on the outermost, middle third of the upper canopy foliage of 12 matured, fully expanded, and sunlit leaves (Hu et al. 2007; Keel et al. 2007). Each year, data was collected using an SC-1 leaf porometer (ICT international, Armidale, NSW, Australia) during the sunny spring (February or March) and summer (August or September) seasons (Hu et al. 2007; Keel et al. 2007; Mccutchan and Shackel 1992). To avoid extreme-high late afternoon temperatures and low relative air humidity, gs was measured around midday (1200 to 1300 h) (Mccutchan and Shackel 1992).

The stem water potential (ψ)

In the spring and summer of the 2021 and 2022 growing seasons, the midday y was measured on two mature, healthy, fully expanded leaves. The leaves were chosen

from the tree canopy's outermost, middle layers with southwest orientation, and fully sunlit leaves (Barkataky et al. 2013; Mccutchan and Shackel 1992). To equilibrate the ψ of the leaves and the stem, the leaves were first covered with a transparent plastic sheath, followed by aluminum foil (Hamido and Morgan 2021; Mccutchan and Shackel 1992). The leaf closest to the trunk was cut from the tree branch and inserted into a pressure chamber piston (Model 3005, Santa Barbara, CA, USA). The y was determined by pumping a 3 MPa pressurized nitrogen (N) gas until water bubbles emerged through the petiole of the leaf (Naor 2000; Scholander et al. 1965).

Leaf nutrient concentrations

During the spring and summer seasons, fifteen to twenty fully expanded mature leaf samples were collected from non-fruiting branches at about two-thirds of the canopy. The samples were washed in a dilute detergent solution (0.1–0.3%, Micro-90 ®Burlington, NJ, USA), rubbed with the thumb and other fingers, and washed with reverse osmosis water, and finally rinsed with deionized water to remove any impurities adhering to the leaf surface. The samples were oven-dried at 65 °C until constant moisture was maintained. Then the samples were ground and passed through a 40-mesh screen using a Wiley mill grinder (Thomas-Wiley Laboratory Mills, Philadelphia, PA, USA).

Leave tissue P, K, Ca, Mg, Mn, Zn, Cu, Fe, and B concentrations were analyzed using the dry ash combustion digestion method (Hanlon et al. 1997; Munter et al. 1984; Morgan et al. 2016). A 0.5-g sample of dried ground leave tissue was weighed and dry ashed at 500 °C for 16 h (Hanlon et al. 1997). The tissue ash was equilibrated with 15 mL of 0.5 M HCl at room temperature for 30 min. The supernatant was transferred into 15 mL plastic tubes and placed in a refrigerator at 4 °C until analyses by inductively coupled plasma analysis (Morgan et al. 2008; Atta et al. 2021). The leaf N concentration was determined using the NA2500 carbon (C)/N Analyzer (Thermoquest CE Instruments; ThermoQuest Corporation, Thermo Fisher Scientific Inc., Waltham, MA, USA).

Leaf area index

Leaf area index (LAI) was measured by a cable-assisted portable LAI meter (Model LI-3000 A LI-COR, Lincoln, NE). The LAI of each tree was estimated using a SunScan canopy device (Dynamax Inc., Houston, TX) during a bright sunny day and by taking the average of the east, west, north, and south directions from the tree trunk (Kadyampakeni et al. 2014b). The BF5 device is a Sunshine Sensor that measures the extent of global and diffuse components of the

incident light captured and penetrated through a tree canopy and sends a signal to the SunScan. Another device called an Emulator mode of the Personal Digital Assistant (PDA) running SunData software simulates SunScan and the BF5 sensor, which ultimately yields the LAI data for each time of the readings.

Minirhizotron root study

Nondestructive root measurement was performed using six transparent minirhizotron tubes installed along the tree rows at 0.5 m from the trunk of a tree. To minimize root damage and soil disruption, the holes were carefully bored with a soil auger (Grainger, Illinois, USA) of 7.5 cm internal diameter (i.d.). The tubes were inserted into the ground at 60°, with the bottom of the tubes sealed with a plastic cup. The top end of the tubes was covered with a detachable cap to prevent water and light from entering the tubes, and the part above the ground was also wrapped with dark and opaque plastic to prevent exposure of the roots to infrared light, which would otherwise impact root growth (Abrisqueta et al. 2008; Han et al. 2016). Root data was collected monthly for two years using a root scanner (CI-600 In-Situ Root Imager, Washington, USA) and processed with Root-Snap Version 1.3.2.25 Release software (CID Bio-Science, Washington, USA). The monthly FRLD data were classified as fine root diameter (d < 2 mm) and coarse root (d > 2 mm), with the fine roots further subdivided into three sub-classes (< 0.5 mm, 0.5–1, and 1–2) (Montagnoli et al. 2018).

Statistics and data analyses

The Stomata conductance, stem water potential, leaf area index, and leaf nutrient concentration data were analyzed using repeated-measures analysis PROC GLM Mixed Model procedures SAS 9.4 (SAS Institute, Cary, NC, USA). Data subjected to spatial, temporal, and other unprecedented variability were tested for the four basic statistical model assumptions: linearity, independence, normality, and homogeneity of variance. Tukey–Kramer honestly significant difference (HSD) grouping range test was used for F-tests with a statistical difference ($p \leq 0.05$) to separate the means. Twelve fine roots per tree ($n = 6$) of fine roots < 2 mm were randomly picked and tracked from the time of appearance until their decay for root survival analyses. The field layout figures were created using BioRender.com and the regression analyses, root survival probability, and median root lifespan were created and analyzed using SSigma Plot 14 (SigmaPlot 14, Systat Software, San Jose, CA, USA). The root survival curves were established using the Kaplan–Meier survival model to test the significant differences

between survival curves within the irrigation rates for the two and three-row tree densities.

Result and discussion

Meteorological information

The average daily minimum, maximum temperatures, and solar radiation for three years (2019 to 2022) were 18.4 (± 4), 29.7 (± 2.9) °C, and 91.4 J m^{-2} s^{-1}, respectively (Fig. 2A). Because temperature is influenced by global radiation, the highest temperature readings were recorded in July and August of the study years. The aerodynamic factor responsible for the increased temperature is solar radiation, in which case the minimum and maximum average reference evapotranspiration (ETo) were recorded in July and December with daily ETo of 1.55 and 4.56 (± 1.0) mm day^{-1}, respectively (Fig. 2B). A decade of historical data (2011–2021) revealed that Southwest Florida had an annual total rainfall record of 1281.4 mm per year. Florida is known for its warm and humid subtropical climate with a bimodal rainfall pattern. The maximum rainfall season lasts from May to October and accounts for more than 80% of the annual precipitation(Kiggundu et al. 2012). The data indicated that the agroclimatic factors (solar radiation, temperature, relative air humidity, and wind speed) used to extrapolate the ETo using the FAO Penman-Monteith method followed a similar pattern to the weather data observed during the study period(Morgan et al. 2006; Kiggundu et al. 2012; Hamido and Morgan 2021).Therefore, the irrigation volume was determined based on ETc with its peak in July and August. Accordingly, the total volume of irrigation applied was the highest in the dry season around May and April, dropped around June and July (rainy season), and again a brief rose in in August. Florida has inherently a bi-modal precipitation pattern in which the precipitation peaks in June and July with brief cessation in August and rises in late September (Atta et al. 2022; Kiggundu et al. 2012). Consequently, the irrigation system was designed on a bi-weekly basis after taking into consideration the agroclimatic weather conditions mentioned above to increase soil moisture content based on the seasonal crop water requirement.

Water relations

Soil moisture content

Volumetric soil water content measurements based on real-time agroclimatic historical data have long been implemented for enhanced irrigation management in reference to crop water demand (Abrisqueta et al. 2008; Hamido and Morgan 2021). Volumetric soil moisture content on the lowest tree density (360 tree ha^{-1}) and moderate irrigation (78%-ET$_c$) revealed that upper soil profiles (0–15, 15–25, 25–35, and 35–45 cm) were within saturated and permanent wilting point ranges during the drier months (Jan.–May) but not during the rainy months (Fig. 3A). All soil profiles below 45 cm were above the field capacity when the trees received the grower standard irrigation (100%-ET$_c$) within the same tree density as above, indicating over-irrigation triggered infiltration regardless of the season (Fig. 3B). The soil profiles, 45–85 cm, were above the field capacity of sandy soils during the summer months. The causes for exceeding the volumetric soil content beyond the field capacity could be either precipitation infiltration and /or excessive irrigation, or a rise in the water table through a capillary action. During the peak rainy season, the topmost soil layer (0–15 cm) reached around field capacity even though the trees were at maximum crop water demand (ETc), highest evapotranspiration, peak solar radiation, and daily air temperatures. This could be due to poorly drained Spodosols, rising water tables, flooding rain events, and growers' excessive irrigation cultural practices. Spodosols are characterized as shallow horizons, the first subsoil horizon, is commonly a white or light gray, poorly drained, nearly level (< 2%), that is particularly low in fertility and water holding capacity (Morgan and Graham 2019; Kadyampakeni and Morgan 2020; Ferrarezi et al. 2020). The volumetric soil water was at the saturation point below 65 cm and 45 cm soil profiles in the moderate tree density (485 tree ha^{-1}) regardless of the season when the trees received moderate (Fig. 3C) and grower standard (high) irrigation (Fig. 3D), respectively. When the trees received moderate irrigation, the soil above 45 cm demonstrated a consistent volumetric soil moisture pattern throughout the year. On the contrary, the volumetric soil water content peaked in the rain seasons for the 25–35 and 35–45 cm soil horizons and below in the grower's standard high irrigation practice, most likely due to rainwater infiltration, reduced evapotranspiration due to closed foliage canopy shadow, or a rise in the water table. A similar volumetric soil-moisture pattern was detected whereby the soil moisture exceeds the field capacity whenever the grove receives rain events (Ferrarezi et al. 2020; Ayankojo and Morgan 2021).

Unlike the low and moderate (two-row grove) tree densities, the highest (three-row grove) tree density (920 tree ha^{-1}) had a higher soil moisture content in the soil saturation zone even at the surface layer (0–15 cm) with deficit irrigation (50%-ET$_c$) during the rainy seasons (Fig. 4A). Soil profiles 65 cm, 55 cm, and 35 cm and below were at soil saturation point even during the dry season for the deficit, moderate (Fig. 4B), or the highest (grower) standard irrigation rates (Fig. 4C and D), respectively. As a result, careful
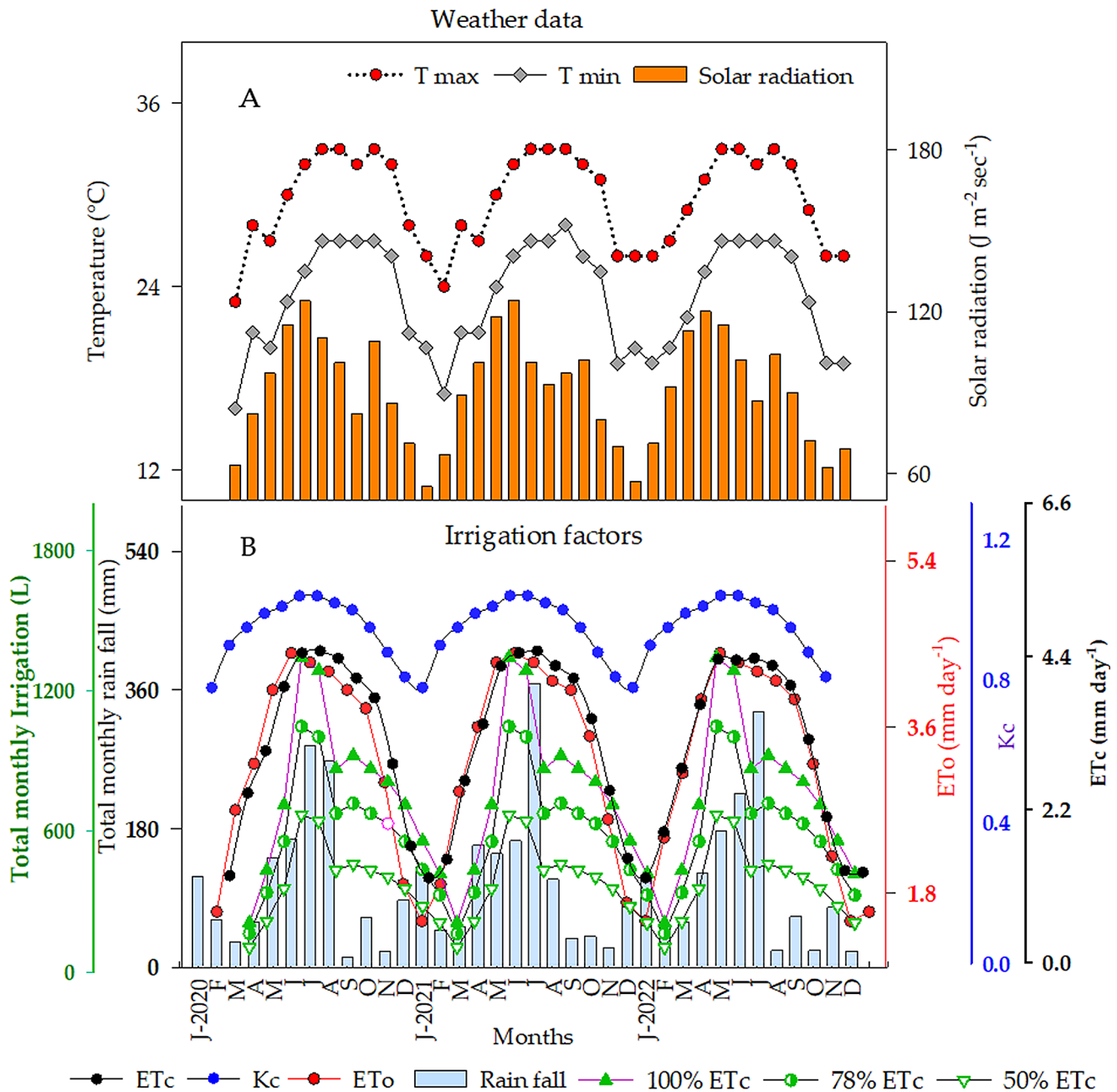
Fig. 2 Monthly average temperature (minimum and maximum) and solar radiation (panel A), total monthly irrigation applied, precipitation, average monthly reference evapotranspiration (ETo), citrus crop coefficient (Kc), and crop evapotranspiration (ETc) (panel B) of the study site

irrigation management is a necessity to control irrigation, which may otherwise lead to infiltration of excess water and nutrients below the reach of the root zone during the dry season and aggravate the rapid buildup of the water table beneath the trees. The root cause of high soil volumetric water content storage could be due to overlapped irrigation wetting patterns and reduced evapotranspiration due to high tree density. Previous studies indicated that heavy rainfall and over-irrigation may result in the leaching of N and P

into the groundwater, anoxic conditions, nutrient discharge beyond the root zone, and decreased crop yields even when nutrients are applied at recommended rates (Morgan et al. 1999; Kiggundu et al. 2012; Morgan et al. 2020; Suresh et al. 2023).

Linear regression analyses of soil volumetric water content in reference to the irrigation applied to meet daily crop water requirements revealed a significant relationship ($R^2 = 0.44$ and $P < 0.001$) or ($R^2 = 0.20$ and $P < 0.01$) in the
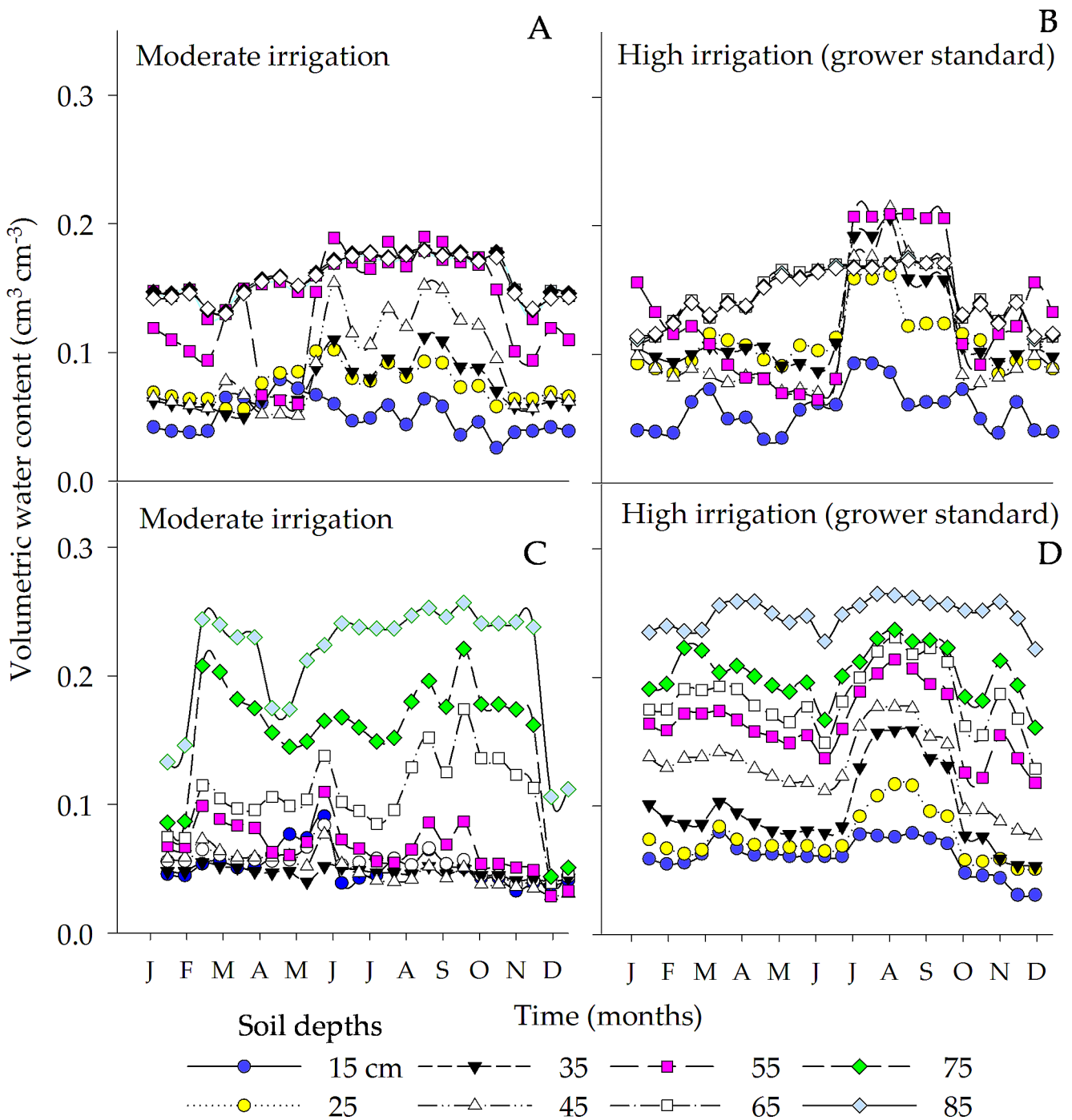
Fig. 3 Daily mean volumetric soil moisture content at moderate (78%-ETc) and high (100%-ETc) irrigation rates in a two-row citrus grove with 360 and 485 trees ha^{-1} panels A and B and C and D, respectively

360 trees ha^{-1} when trees received moderate or grower standard high irrigation rates, respectively (Fig. 5A and B). The linear relationship of the soil volumetric water content in reference to meeting the daily crop water requirement had ($R^2 = 0.30$ and $P < 0.01$) or ($R^2 = 0.44$ and $P < 0.001$), respectively with a tree density of 360 trees ha^{-1} and when trees received moderate or grower standard high irrigation rates

(Fig. 5C and D). The predicted and observed soil moisture values for both tree densities remained within the plant's available water ranges of permanent wilting point and field capacity. Meanwhile, the regression analyses of soil volumetric water content and the daily crop water requirement had ($R^2 = 0.21$ and $P < 0.01$), ($R^2 = 0.51$ and $P < 0.001$), or ($R^2 = 0.10$ and $P = 0.06$), for the deficit (Fig. 6A), moderate
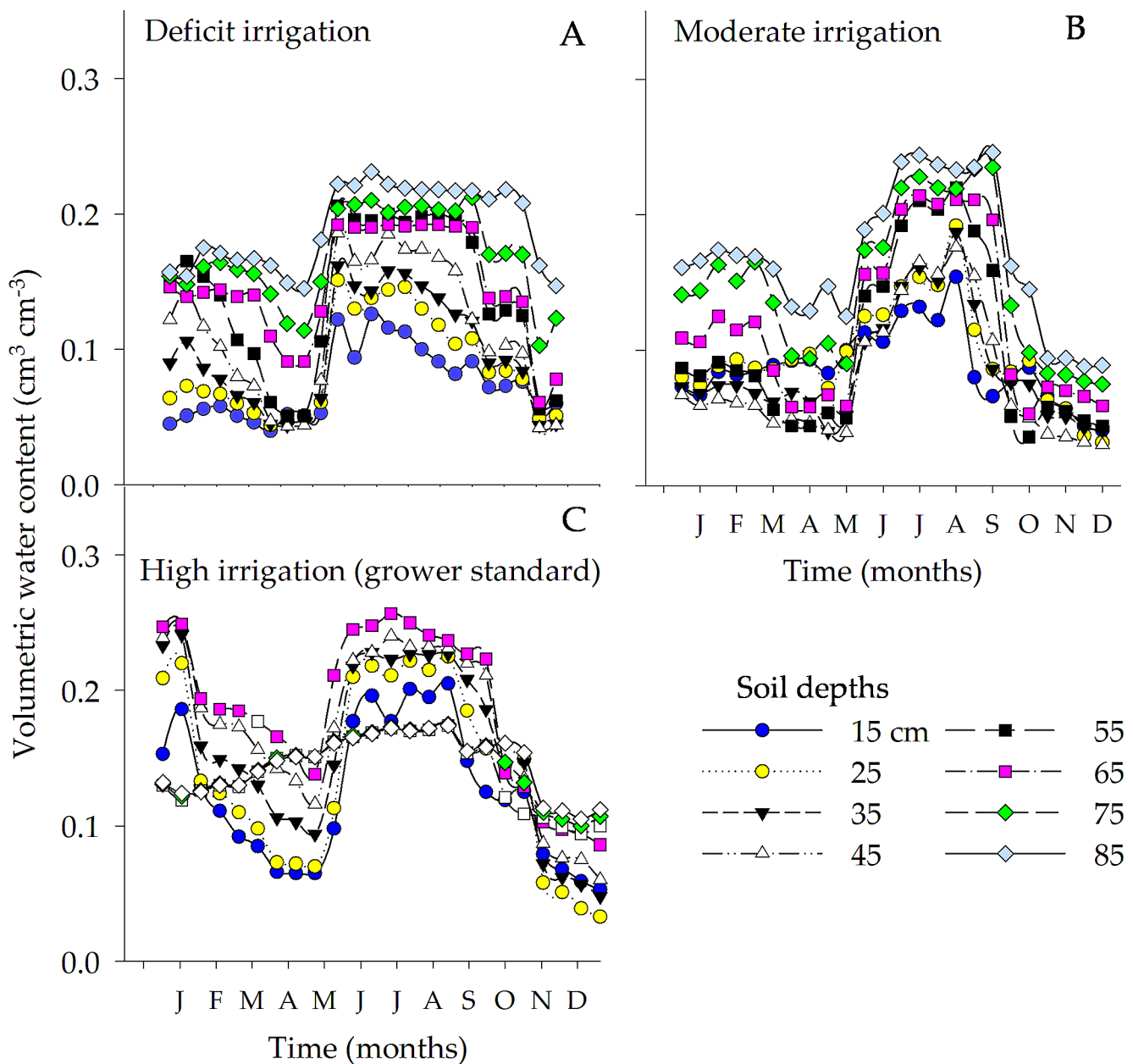
Fig. 4 Daily mean volumetric soil moisture content of a three-row citrus grove with 920 trees ha^{-1} of deficit (50%-ETc), moderate (78%-ETc), and high (100%-ETc) irrigation rates panels **A**, **B**, and **C**, respectively

(Fig. 6B), or grower standard (Fig. 6C) in the highest tree density, respectively. During the rainy season with high crop water demand, some observed values of volumetric soil water content were above the field capacity due to over-irrigation, flooding rain events, and rising water table despite irrigation rates. Volumetric soil water content was above the field capacity in some instances of high rainfall combined with over-irrigation and rising water table during the spring and rainy seasons. This indicates that the irrigation rate of 100%-ET$_c$ was excessive in the three-row groves.

Stomata conductance and stem water potential

Stomata conductance (*gs*) showed a significant interaction effect between season × tree density (*p* < 0.0001) and tree density × irrigation rates (*p* < 0.05) (Table 1). In the spring season, the *gs* was significantly higher when the trees received moderate irrigation rather than the highest (grower standard) rate in the lowest tree density. The reason for higher *gs* in the lowest tree density in the spring and rainy seasons could be increased FRLD with improved moderate irrigation rate than grower standard higher irrigation
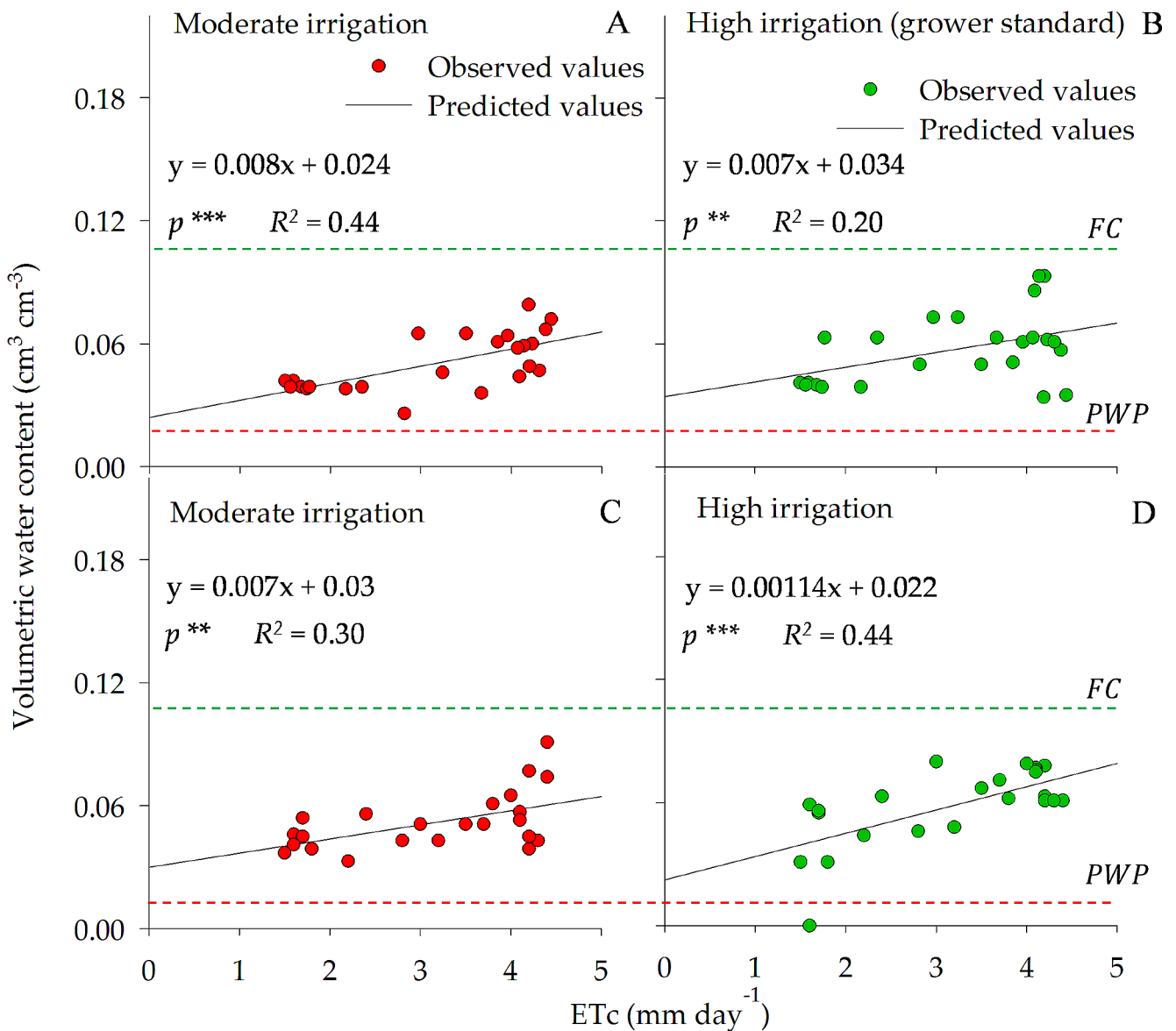
Fig. 5 Linear regression analyses of a two-row citrus grove at moderate (78%-ETc) and high (Grower standard) irrigation rate (100%-ETc) based on crop-water requirement and soil volumetric water content of 0–15 cm soil horizon in response to daily irrigation at 360 and 485 trees ha^{-1}panels (**A** and **B**) and (**C** and **D**), respectively. Horizontal dashed-line in green soil at field capacity (FC) and red soil at permanent witling-point (PWP)

rates, which will be discussed later. Because soil moisture was higher in the summer than in the spring season, the seasonal variation in *gs* is more evident. In the spring season, it was also barely noticeable to observe a significant *gs* despite tree density among the deficit, moderate, or highest (grower standard) irrigation rates. The rainy season had the highest stomata conductance, with the lowest tree density in the spring and moderate irrigation rates in the summer. This high stoma conductance in moderate tree density could be due to overlapping irrigation wetting patterns and reduced evapotranspiration caused by the high tree density, which shields the soil from direct solar radiation and blowing air

current as previously mentioned. Moreover, the lower *gs* at the highest tree density could also be the rise in Ca^{2+} concentration or close the stomatal aperture in response to the elevation in extracellular Ca^{2+} concentration (Dayod et al. 2010; Gilliham et al. 2011).

The stem ψ (a manifestation of water stress) was significantly affected by the interaction effects between season × tree density ($p < 0.0001$) and tree density × irrigation rates ($p < 0.0001$), in which trees were significantly stressed in the highest tree density as compared with the moderate and lowest tree densities in the spring season (Table 1). However, in the spring season, the trees were more stressed in
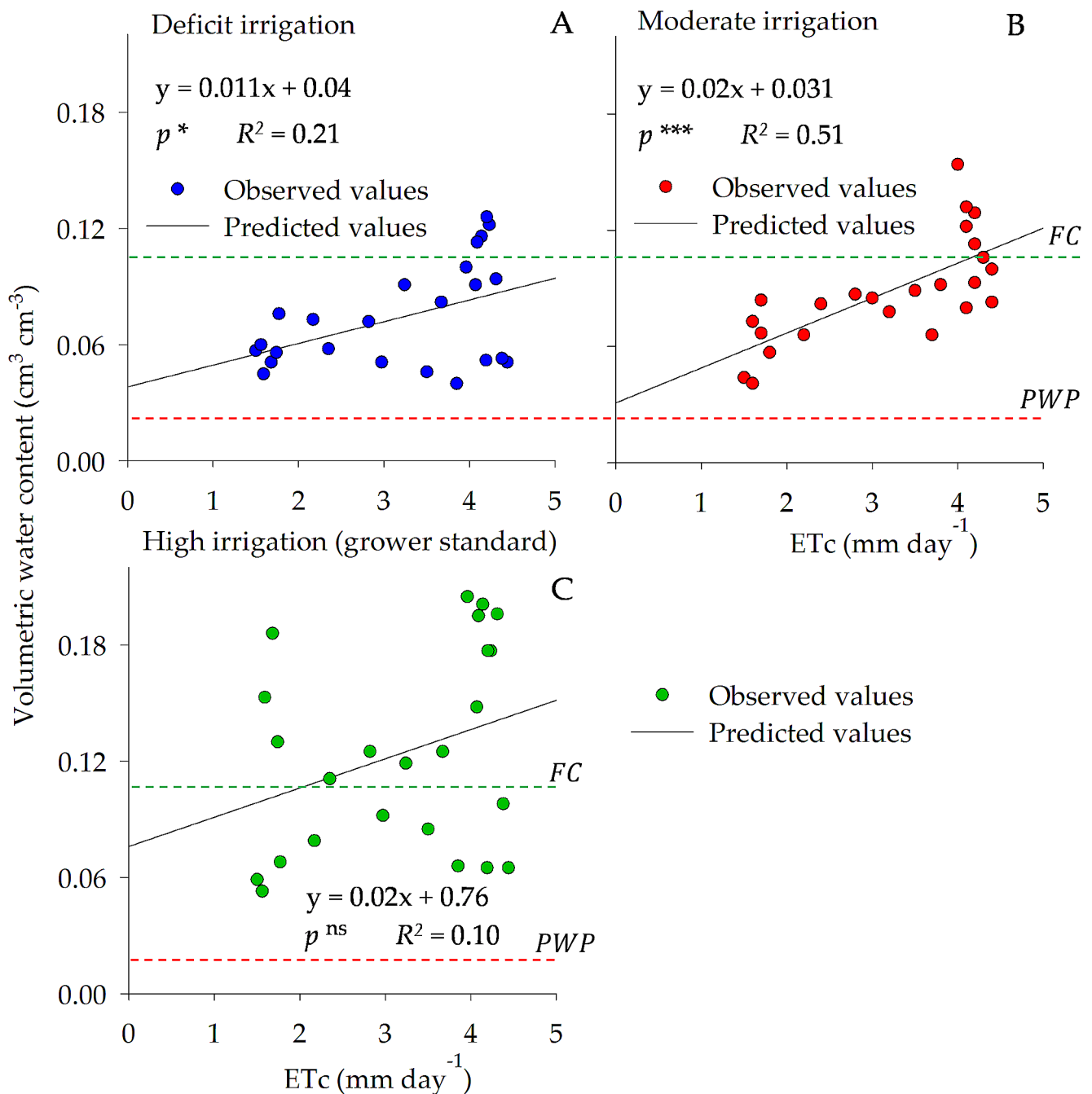
Fig. 6 Linear regression analyses of a three-row citrus grove at three irrigation rates: deficit (50%-ET_c) panel (**A**), moderate (78%-ET_c) panel (**B**), and high irrigation (100%-ET_c) panel (**C**) and volumetric soil moisture content of 0–15 cm soil horizon in reference to the daily irrigation applied at 920 trees ha^{-1} tree density during 2019–2022 growing seasons. Horizontal dashed-line in green soil at field capacity (FC) and in red soil at permanent witling-point (PWP)

the highest grower standard irrigation than with moderate and deficit irrigation rates. The stressful instances in the highest tree density in the spring could be due to competition for soil moisture, which is more evident in the highest tree density than in moderate and lowest tree density. Even the stress in a higher irrigation rate than a moderate irrigation rate could be that moderate irrigation triggered

more fine roots, allowing the trees to overcome the stress by investing more in fine roots for soil moisture uptake. Previous studies indicated that although a higher irrigation rate (100%-ET_c) guaranteed higher soil moisture contents, trees that received a lower irrigation rate (62%-ET_c) did not correspond to biological stress because of irrespective of planting density, a result supported by the pertinent stem

Table 1 Stomata conductance and stem water potential of Valencia citrus trees at different tree densities and irrigation rates

		Stomata conductance (mm m^{-2} s^{-1})			Stem water potential (Mpa)		
		Tree density (trees ha^{-1})					
Season	Irrigation rate [1]	360	485	920	360	485	920
Spring	Deficit			139.4a			1.99a
	Moderate	164.0a [2]	160.9a	145.7a	1.18aA	1.52aB	1.93aC
	High	91.6b	170.9a	173.4a	1.56bA	1.56bA	2.01aB
Summer	Deficit			267.2a			1.26a
	Moderate	490.2aA	476.4aB	322.3aC	1.44a	1.63a	1.27a
	High	159.4aC	490.2 A	343.2aB	1.61b	1.42a	1.28a
Model effect [3]		ANOVA					
S		***			***		
D		***			***		
I		ns			***		
S × D		***			***		
D × I		*			*		

[1] Irrigation rates: Deficit = 50%-ET$_c$, Moderate = 78%-ET$_c$, and High = 100%-ET$_c$. [2] Values on vertical columns for irrigation rate followed by different (lower case letters) and across the rows (upper case letters) for tree density are significantly different at $p < 0.05$, according to Tukey's honestly significant difference test. [3] Model effects: S = season of the year, spring (dry) and summer (wet) seasons, D = tree densities, I = irrigation rates

ψ (Hamido and Morgan 2021). When the tree received the highest or grower standard irrigation rates, the moisture stress decreased in summer compared with the moderate and lowest tree density. Partial drying (aka lower as compared with grower standard higher irrigation rates) triggers FRLD which in turn boosts water uptake efficiency. Like the current study, previous studies indicated that lower irrigation rates retained the plant water status closer to the optimal levels (Shahnazari et al. 2007; Hutton and Loveys 2011; Hamido and Morgan 2021).

Leaf nutrient concentration

Leaf nutrient concentrations of Ca, Mn, Zn, and Fe were deficient in the moderate and highest tree densities according to the optimum ranges for Florida citrus nutrition, Leaf Ca concentration was deficient in the highest tree density only when the trees received deficit or moderate irrigation rates, and it was deficient in the moderate tree density only when trees received moderate irrigation rates (Table 2). This indicated that when there was excess moisture in the soil, the Ca nutrient concentration in the leaves was higher. A steady flow of Ca^{2+} from the roots to the shoots along the transpiration stream probably led to elevated Ca^{2+} concentrations in leaves especially in the guard cells has been associated with the closure of stomata (Dayod et al. 2010; Gilliham et al. 2011).

Regardless of irrigation rate, uptake and leaf Mn concentrations were deficient in all tree densities. Similarly, regardless of the irrigation rate, leaf Zn concentration was below the optimum nutrient range in moderate tree densities. The reason for the deficient leaf Mn and Zn concentrations could be because of nutrient leaching below the root zone or dilution effect because of mass vegetative growth, as shown by the leaf area index when compared to the lowest and highest tree densities. Leaf Fe nutrient concentration was also deficient when the trees received moderate irrigation rather than the highest grower standard irrigation rates.

Leaf area index

Results indicated that the LAI didn't show a significant effect on the various irrigation regimes in the current study in the two-row groves (Fig. 7A and B). On the other hand, there were significant effects ($p = 0.0186$) as trees received varying irrigation rates in the three-row (high-density) grove (Fig. 7C). LAI is the manifestation of the within and the under-canopy microclimate, which influences and governs canopy water interference, radiation interception, water, and carbon gas interactions, and plays a vital role in the ecosystem and biogeochemical cycles (Bréda 2003; Atta et al. 2022). The variation in LAI was depicted in the three-row groves because the trees were closely planted and interacted in the soil and above ground in response to soil moisture variability and various aerodynamic factors. Accordingly, those trees that received moderate irrigation rates showed 53% and 44% more LAI than the deficit and grower-standard higher irrigation rates, respectively. These findings were similar to results found for the FRLD in which case root survival probability and median root survival (discussed in the following section) were significantly affected in the three-row groves when trees received moderate irrigation rates than the deficit and grower standard highest irrigation rates.

Table 2 Leaf nutrient concentration of Valencia citrus trees at three tree densities and irrigation rates: deficit (50%-ET_c), moderate (78%-ET_c), and high irrigation (100%-ET_c)

Leaf tissue nutrients	Irrigation rate [1]	Tree densities (trees ha^{-1})			Optimum nutrient ranges [4]
		360	485	920	
N	Deficit			3.41ab*[2]	
	Moderate	3.25aA	3.31bB	3.53aA°[3]	2.5–2.7
	High	3.13aA	3.08bB	3.3bA°	
P	Deficit			0.15b***	
	Moderate	0.15aA	0.17aA	0.16aA	0.12–0.16
	High	0.15aB	0.16aA	0.13cC°°	
K	Deficit			1.56a***	
	Moderate	1.32aB	1.35aAB	1.47bA°	1.20–1.70
	High	1.27aA	1.36aA	1.25cA	
Ca	Deficit			2.56b***	
	Moderate	3.3aA	2.9bB	2.58bB°°	3.0–4.0
	High	3.3aA	3.1aB	3.2aA°	
Mg	Deficit			0.23a	
	Moderate	0.26 A	0.28aA**	0.23aB°°°	0.20–0.29
	High	0.26 A	0.26bA	0.22aB°°	
Mn	Deficit			64b***	
	Moderate	37aB	17aC	57cA°°°	25–100
	High	32aB	17aC	70aA°°°	
Zn	Deficit			53b***	
	Moderate	41aAB	24aB	44bA°	25–100
	High	48aB	24aC	85aA	
B	Deficit			62b***	
	Moderate	73aA	63aA	68bA	36–100
	High	67aB	67aB	76aA°°	
Fe	Deficit			67b**	
	Moderate	72aAB	57aB	77abA°	60–120
	High	68aB	60aC	82aA°°°	
Cu	Deficit			13b***	
	Moderate	24aA	14aB	14bB°	5.0–16
	High	25aB	15aC	36aA°°°	

[1]Irrigation rates: deficit (50%-ET_c), moderate (78%-ET_c), and high irrigation (100%-ET_c). [2]The asterisks: *, **, and *** along the vertical columns indicate significance among the irrigation rates at $p \leq 0.05$, < 0.01, and < 0.0001, respectively. [3] The degrees: °, °° and °°°across the horizontal lines indicate significance among the tree densities at $p \leq 0.05$, < 0.01, and < 0.0001, respectively. [4]Optimum nutrient ranges indicate the critical leaf nutrient range for Florida citrus nutrition

Fine root length density and lifespan

In the two-row and lowest tree density, moderate irrigation produced significantly more FRLD than grower standard high irrigation. Moderate irrigation rates also had higher FRLD than high irrigation rates (Fig. 8A and B). Fine (0.5–2.0 mm) and coarse roots (> 2.0 mm) were clearly distinguished in the high irrigation rates as well. More FRLD persisted after the rainy season ended, indicating that roots acclimated to moderate irrigation were more responsive to adverse soil moisture contents than the grower standard high irrigation rates. Variation in fine and coarse roots in

two-row groves with moderate tree densities is not noticeable regardless of the irrigation rates (Fig. 8C and D). However, fine roots (< 0.5–1.0 mm) disappeared after the rainy months resulting in higher irrigation rates in the moderate tree density. Only during June and July months when the finest root (< 0.5 mm) has significantly the highest FRLD for the moderate irrigation rates in the moderate tree density. When trees were accustomed to moderate irrigation rather than growers' standard irrigation rates, fine roots were more reactive to soil moisture stress. The growth of fine root (< 0.5 and 0.5–1.0 mm) in the three-row tree densities was interrupted when the trees adapted to the two extreme irrigation rates, deficit (Fig. 9A) and grower standard highest (Fig. 9C) irrigation rates rather than moderate irrigation rates (Fig. 9B). Trees grown under grower standard high irrigation invest poorly in the root system to adapt for extensive root growth because water is perpetually within the reach of roots year-round.

According to the Kaplan–Meier root survival (lifespan) analyses, significant root survival rates were detected in the lowest ($p < 0.001$) and highest ($p < 0.001$) tree densities when the trees received moderate irrigation rate than deficit or grower standard highest irrigation rates (Fig. 10A–C). These results were consistent with the fine root length densities, which showed that the trees had higher root density at moderate irrigation rates than at deficit or grower standard irrigation rates. In the moderate tree density, there was no difference in the survival probability when the trees received either deficit or grower standard irrigation rates. This implied that reducing or increasing irrigation (grower standard) increased the fine root turnover rate more than moderate irrigation rates in the lowest and highest tree densities than moderate tree density.

In the lowest two-row ($p < 0.001$) and three-rows highest tree density ($p < 0.001$) groves, the median root survival or lifespan, the root survival probability at which the root survival rate is 50%, was significantly higher in moderate irrigation than in the grower standard highest irrigation rates (Fig. 10D–F). The median root survival rates were again in line with the FRLD and survival probability. Regardless of irrigation rates, no significant effects were found for root survival probability and median root survival rates in moderate tree densities in the two-row groves. The results showed that when the trees received moderate irrigation rates in the lowest tree densities or moderate irrigation rates rather than deficit irrigation rates in the highest tree density the median root survival was 35% and 54% higher, respectively. The median root lifespan of the two-row grove was reported to be 235 d and 173 d and 195 and 175 d for the moderate and grower standard (highest) irrigation rates for the 360 and 485 trees ha^{-1} tree densities, respectively. Meanwhile, the median root lifespan of the three-row grove

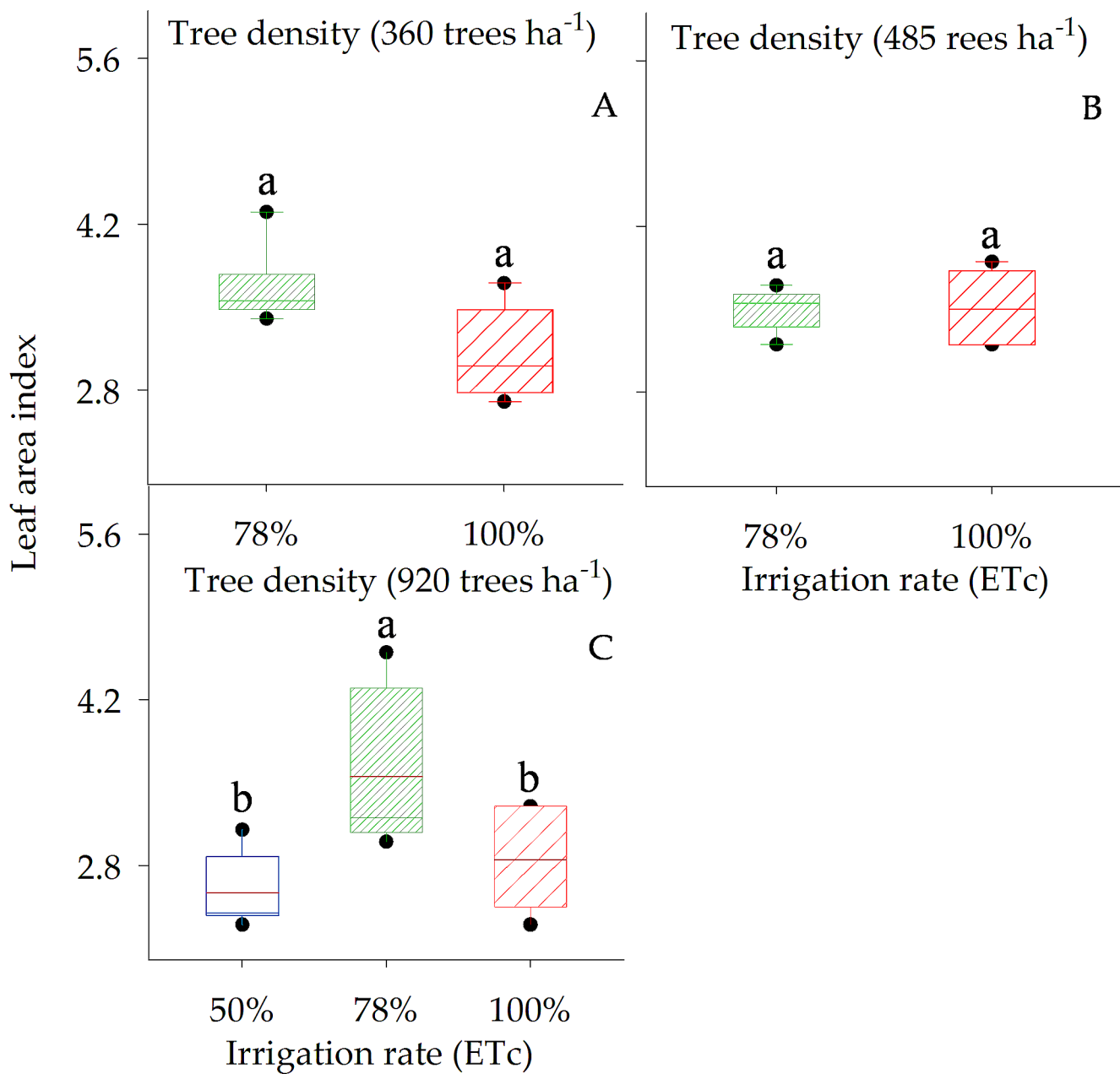**Fig. 7** Leaf area index of two-row citrus groves at the moderate (78%-ET$_c$) and high (100%-ET$_c$) irrigation rates (**A** and **B**) and three-row grove with a deficit (50%-ET$_c$), moderate (78%-ET$_c$), and high (100%-ET$_c$) irrigation rates panels **C**

of 920 trees ha^{-1} tree densities was 118 d, 182 d and 150 d for the deficit, moderate, and grower standard (highest) irrigation rates, respectively. The results of this study were similar to a recent study on young citrus trees under varying irrigation treatments indicating that the mean root lifespan using the Kaplan–Meier survival analysis was estimated to be 153 and 150 d for 62% and 100%-ET$_c$ irrigation rates, respectively (Hamido and Morgan 2020). The median root lifespan of healthy Valencia citrus trees was reported to be about (0.25–0.5 mm) 131 and 111 d(Wells et al. 2002) and 113 days d for fine roots d < 0.5 mm and 226–259 days for

fine roots > 1 mm(Wells and Eissenstat 2002; Kumar et al. 2018) and HLB-affected citrus was reported to be about 61 days(Atta et al. 2020b) and Peach, Prunus persica was 77 days (Wells et al. 2002). Based on the current and previous findings results indicated that higher-order roots and lower irrigation rates had greater survival rates and median root life span than lower-order and higher irrigation rates. The shorter life span of the finest roots could also be their transformation to the next root order as they grow and get older.
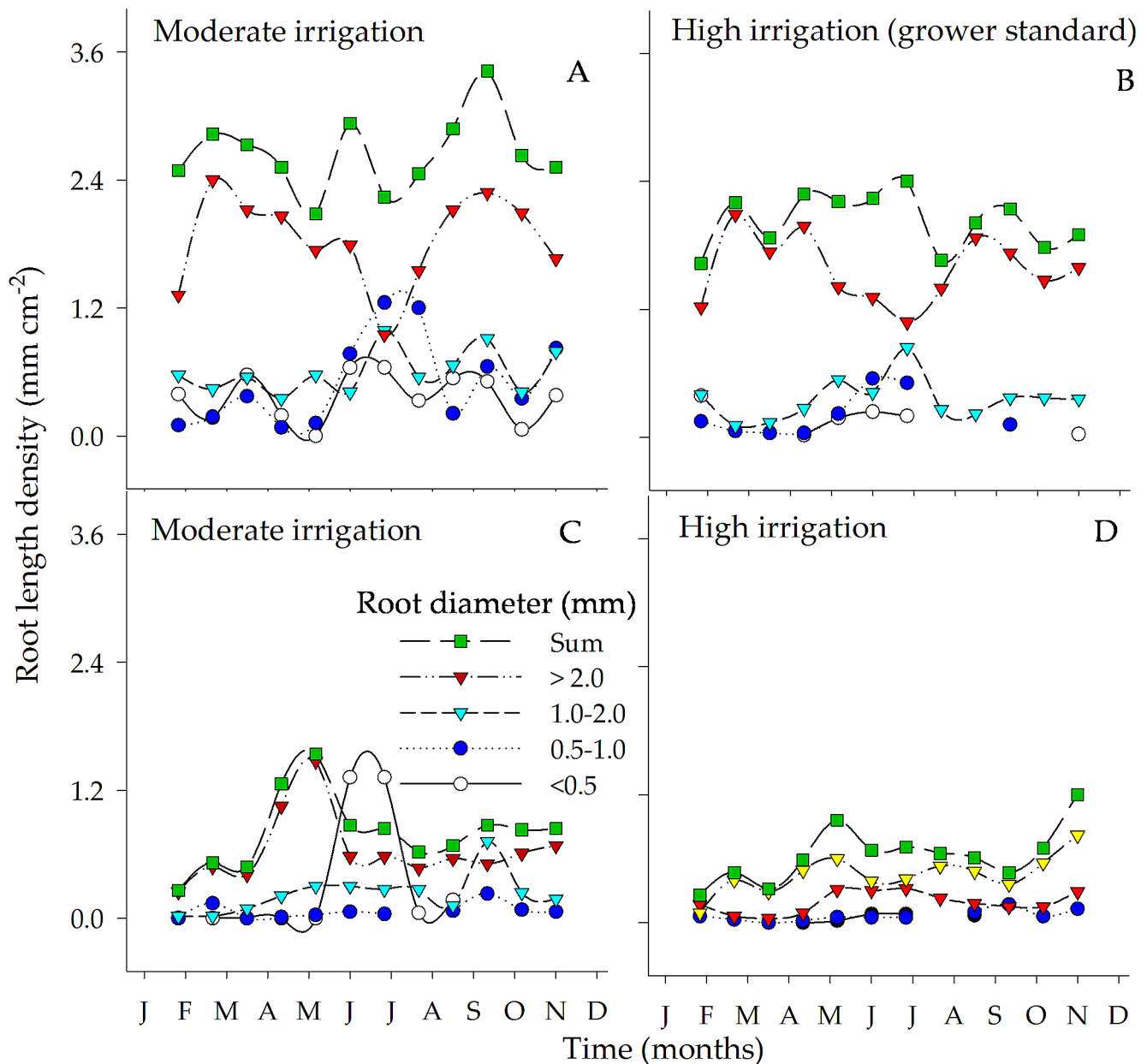
Fig. 8 Fine root length density at moderate (78%-ET$_c$) and high (100%-ET$_c$) irrigation rates panels in a two-row citrus grove in a 360 and 485 trees ha^{-1} of panels **A** and **B** and **C** and **D**, respectively

Conclusion

With increasing the demand for water quality concerns, researchers devised novel irrigation practices for better water management and other environmental issues. The current findings indicated that 20–30% less irrigation rates as compared with grower standards indicating that moderate irrigation rates had better soil-wetting patterns year-round across the various soil profiles with emphasis on the exploitation of rainfall and underground soil water resources. Moreover, stomata conductance and stem-y indicated that trees showed less stress to soil moisture when the trees received moderate irrigation irrespective of tree densities. Thus, lower stress had in turn significant impact on the proliferation of FRLD and LAI above-the-ground tree growth. Moderate irrigation rates not only triggered FRLD but also improved root survival probability and lifespan. Meanwhile, the uptake of the nutrients from the soil had significant effects on leaf nutrient concentration when trees received moderate irrigation than deficit or highest irrigation rates.
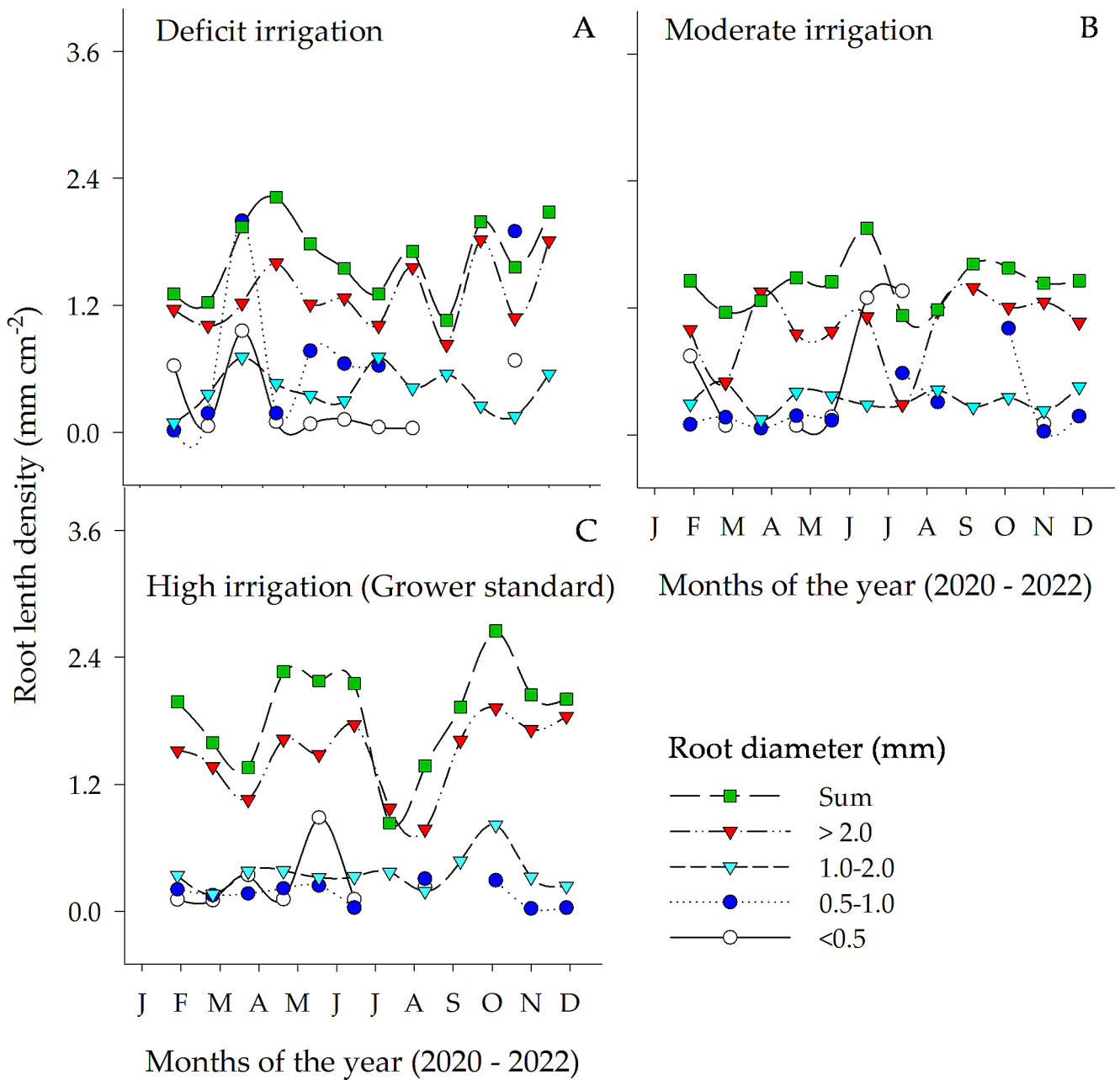
Fig. 9 Fine root length density in three-row citrus groves with a tree density of 920 trees ha^{-1} tree density with a deficit (50%-ET$_c$), moderate (78%-ET$_c$), and high (100%-ET$_c$) irrigation rates panels **A** and **B** and **C** and **D**, respectively
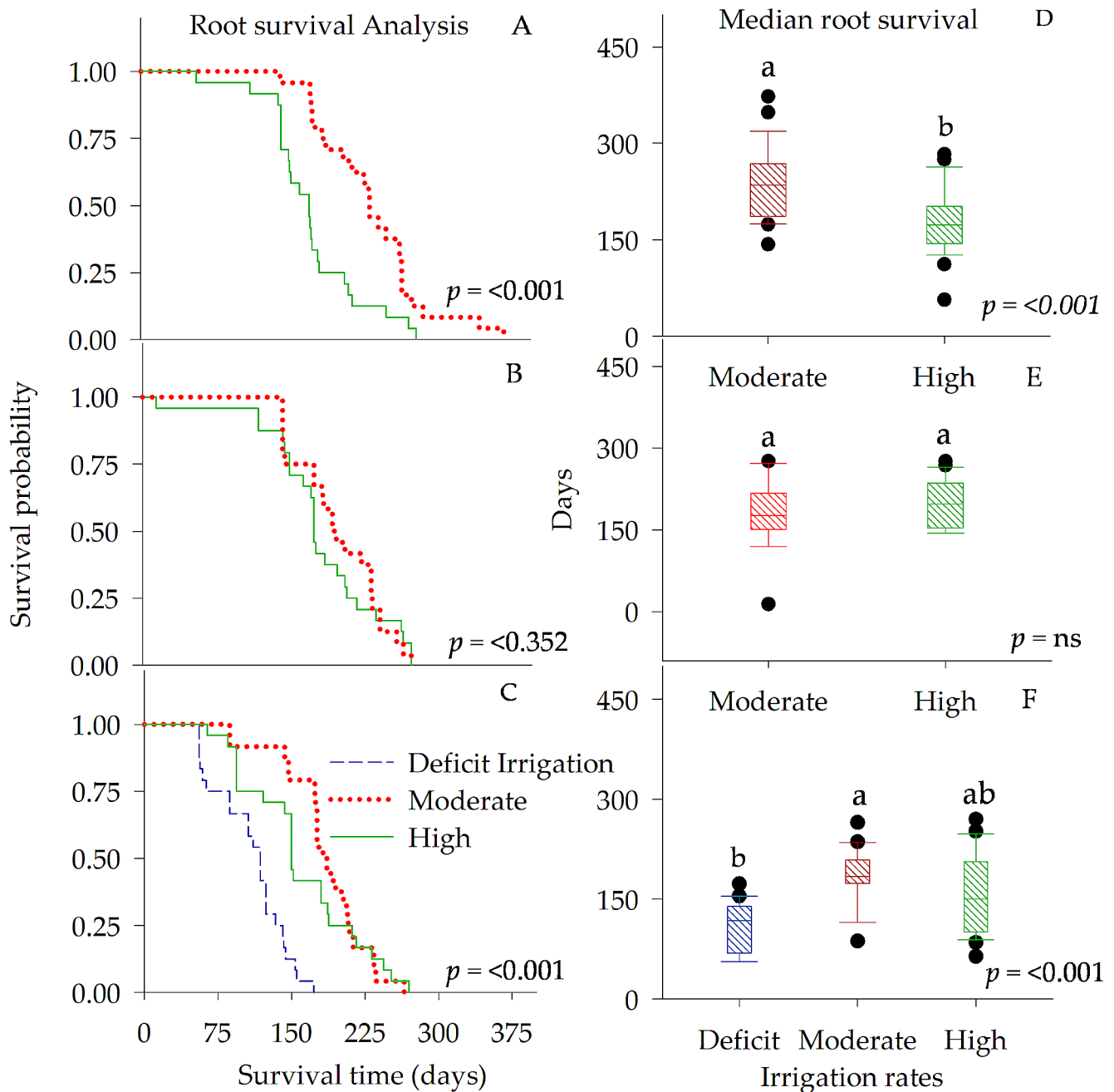
Fig. 10 Kaplan–Meier root survival (lifespan) curve and median root survival analyses of deficit (50%-ET$_c$), moderate (78%-ET$_c$), and high (100%-ET$_c$) irrigation rates in 360, 485, and 920 trees ha^{-1} tree densities panel **A** and **D**, **B** and **E**, and **C** and **F**, respectively

Declarations

References

Abrisqueta JM, Mounzer O, Álvarez S et al (2008) Root dynamics of peach trees submitted to partial rootzone drying and continuous deficit irrigation. Agric Water Manag 95:959–967. https://doi.org/10.1016/j.agwat.2008.03.003

Allen RG, Pereira LS, Raes D, Smith M (1998) Crop evapotranspiration. Guidelines for computing crop water requirements. FAO Irr Drain Paper 56

Atta AA, Morgan KT, Hamido SA, Kadyampakeni DM (2020) Effect of essential nutrients on roots growth and lifespan of huanglongbing affected citrus trees. Plants 9. https://doi.org/10.3390/plants9040483

Atta AA, Morgan KT, Mahmoud KA (2021) Split application of nutrients improve growth and yield of Huanglongbing-affected citrus trees. Soil Science Society of America Journal 1–14. https://doi.org/10.1002/saj2.20310

Atta AA, Morgan KT, Kadyampakeni DM (2022) Spatial and Temporal Nutrient Dynamics and Water Management of Huanglongbing-affected mature Citrus trees on Florida Sandy Soils. Sustain (Switzerland) 14. https://doi.org/10.3390/su14127134

Ayankojo IT, Morgan KT (2021) Optimizing tomato growth and productivity using nitrogen and irrigation application timing. Agronomy 11. https://doi.org/10.3390/agronomy11101968

Ayankojo IT, Morgan KT, Kadyampakeni DM, Liu GD (2020) Tomato growth, yield, and root development, soil nitrogen and water distribution as affected by nitrogen and irrigation rates on a Florida sandy soil. HortScience 55:1744–1755. https://doi.org/10.21273/HORTSCI15177-20

Barkataky S, Ebel RC, Morgan KT, Dansereau K (2013) Water relations of well-watered citrus exposed to cold-acclimating temperatures. HortScience 48:1309–1312

Barooah P, Alvi M, Ringler C, Pathak V (2023) Gender, agriculture policies, and climate-smart agriculture in India. Agric Syst 212. https://doi.org/10.1016/j.agsy.2023.103751

Bodaghi S, Pugina G, Meyering B, Bowman KD Albrecht U (2022) Different sweet orange–rootstock combinations infected by Candidatus Liberibacter asiaticus under Greenhouse Conditions: effects on the roots. HortScience 57:56–64. Retrieved May 20, 2024, from https://doi.org/10.21273/HORTSCI16206-21

Bréda NJJ (2003) Ground-based measurements of leaf area index: a review of methods, instruments and current controversies. J Exp Bot 54:2403–2417

Cui M, Zeng L, Qin W, Feng J (2020) Measures for reducing nitrate leaching in orchards: a review. Environ Pollut 263:263: 1–15. https://doi.org/10.1016/j.envpol.2020.114553

Dayod M, Tyerman SD, Leigh RA, Gilliham M (2010) Calcium storage in plants and the implications for calcium biofortification. Protoplasma 247:215–231

Ferrarezi RS, Nogueira TAR, Zepeda SGC (2020) Performance of soil moisture sensors in Florida Sandy Soils. Water (Switzerland) 12. https://doi.org/10.3390/w12020358

García Petillo M, Castel JR (2007) Water balance and crop coefficient estimation of a citrus orchard in Uruguay. Span J Agricultural Res 5:232–243. https://doi.org/10.5424/sjar/2007052-243

Gasque M, Martí P, Granero B, González-altozano P (2016) Effects of long-term summer deficit irrigation on ' Navelina ' citrus trees. Agric Water Manag 169:140–147. https://doi.org/10.1016/j.agwat.2016.02.028

Gilliham M, Dayod M, Hocking BJ et al (2011) Calcium delivery and storage in plant leaves: exploring the link with water flow. J Exp Bot 62:2233–2250

Graham JH, Johnson EG, Gottwald TR, Irey MS (2013) Presymptomatic fibrous root decline in citrus trees caused by Huanglongbing and potential interaction with Phytophthora spp. Plant Dis 97:1195–1199. https://doi.org/10.1094/PDIS-01-13-0024-RE. PMID: 30722426

Hamido SA, Morgan KT (2020) Effect of various Irrigation Rates on Growth and Root Development of Young Citrus Trees in High-Density planting. 1–27. https://doi.org/10.3390/plants9111462

Hamido SA, Morgan KT (2021) The effect of irrigation rate on the water relations of young citrus trees in high-density planting. Sustain (Switzerland) 13:1–18. https://doi.org/10.3390/su13041759

Hamido SA, Morgan KT, Kadyampakeni DM (2017) The effect of huanglongbing on young citrus tree water use. Horttechnology 27:659–665. https://doi.org/10.21273/HORTTECH03830-17

Han SH, Yun S, Lee J et al (2016) Estimating the production and mortality of fine roots using minirhizotrons in a Pinus densiflora forest in Gwangneung, Korea. J Res (Harbin) 27:1029–1035. https://doi.org/10.1007/s11676-016-0221-6

Hanlon EA, Gonzalez JS, Bartos JM (1997) Institute of Food and Agricultural Sciences (IFAS) Extension Soil Testing Laboratory (ESTL) and Analytical Research Laboratory (ARL) chemical procedures and training manual. Circ, vol 812. Univ. of Florida, Gainesville, FL

Holt N, Sishodia RP, Shukla S, Hansen KM (2019) Improved Water and Economic sustainability with low-input Compact Bed Plasticulture and Precision Irrigation. J Irrig Drain Eng 145. https://doi.org/10.1061/(asce)ir.1943-4774.0001397

Hu LM, Xia RX, Xiao ZY et al (2007) Reduced leaf photosynthesis at midday in citrus leaves growing under field or screenhouse conditions. J Hortic Sci Biotechnol 82:387–392. https://doi.org/10.1080/14620316.2007.11512248

Hutton RJ, Loveys BR (2011) A partial root zone drying irrigation strategy for citrus-effects on water use efficiency and fruit characteristics. Agric Water Manag 98:1485–1496. https://doi.org/10.1016/j.agwat.2011.04.010

Ippolito M, De Caro D, Ciraolo G Estimating crop coefficients and actual evapotranspiration in citrus orchards with sporadic cover weeds based on ground and remote sensing data. Irrig Sci., Morgan TA, Albrigo KT et al (2022) GA, (2020) recommended fertilizer rates and timing, p 51–64. In: Morgan KT, Kadyampakeni DM (eds). Nutrition of Florida citrus trees, Elec. Data Info. Source, SL 462; Univ. of Florida Inst. of Food and Agric. Sci. Gainesville, FL, USA. https://doi.org/10.32473/edis-ss478-2020

Kadyampakeni DM, Morgan KT, Schumann AW, (2014a) Ammonium and nitrate distribution in soil using drip and microsprinkler irrigation for citrus production. Soil Sci Soc Am J 78:645–654. https://doi.org/10.2136/sssaj2013.07.0319

Kadyampakeni DM, Morgan KT, Schumann AW et al (2014b) Water Use in drip- and Microsprinkler-Irrigated Citrus Trees. Soil Sci Soc Am J 78:1351–1361. https://doi.org/10.2136/sssaj2014.02.0054

Kadyampakeni DM, Morgan KT, Schumann AW, Nkedi-kizza P (2014c) Effect of irrigation pattern and timing on Root Density of Young Citrus Trees infected with Huanglongbing Disease. 24:209–221

Keel SG, Pepin S, Leuzinger S, Körner C (2007) Stomatal conductance in mature deciduous forest trees exposed to elevated CO2. Trees - Struct Function 21:151–159. https://doi.org/10.1007/s00468-006-0106-y

Kiggundu N, Migliaccio KW, Schaffer B et al (2012) Water savings, nutrient leaching, and fruit yield in a young avocado orchard as affected by irrigation and nutrient management. Irrig Sci 30:275–286. https://doi.org/10.1007/s00271-011-0280-6

Kumar N, Kiran F, Etxeberria E (2018) Huanglongbing-induced anatomical changes in citrus fibrous root orders. HortScience 53:829–837. https://doi.org/10.21273/HORTSCI12390-17

Mbabazi D, Migliaccio KW, Crane JH et al (2017) An irrigation schedule testing model for optimization of the Smartirrigation avocado app. Agric Water Manag 179:390–400. https://doi.org/10.1016/j.agwat.2016.09.006

Mccutchan H, Shackel KA (1992) Stem-water potential as a Sensitive Indicator of Water stress in Prune Trees (Prunus domestica L. Cv. French). Am Soc Hortic Sci Jashs 117(4):607–611 Retrieved Apr 12, 2024, from. https://doi.org/10.21273/JASHS.117.4.607

Montagnoli A, Terzaghi M, Giussani B et al (2018) An integrated method for high-resolution definition of new diameter-based fine root sub-classes of Fagus sylvatica L. Ann Sci 75. https://doi.org/10.1007/s13595-018-0758-y

Morgan KT, Graham JH (2019) Nutrient status and root density of huanglongbing-affected trees: consequences of irrigation water bicarbonate and soil pH mitigation with acidification. Agronomy 9. https://doi.org/10.3390/agronomy9110746

Morgan KT, Parsons LR, Wheaton TA et al (1999) Field Calibration of a Capacitance Water Content Probe in Fine Sand soils. Soil Sci Soc Am J 63:987–989. https://doi.org/10.2136/sssaj1999.634987x

Morgan KT, Obreza TA, Scholberg JMS et al (2006) Citrus Water Uptake Dynamics on a Sandy Florida Entisol. Soil Sci Soc Am J 70:90–97. https://doi.org/10.2136/sssaj2005.0016

Morgan KT, Zotarelli L, Dukes MD (2010) Use of Irrigation technologies for Citrus Trees in Florida. HortTechnology Hortte 20:74–81 Retrieved Apr 12, 2024, from. https://doi.org/10.21273/HORTTECH.20.1.74

Morgan KT, Rouse RE, Ebel RC (2016) Foliar applications of essential nutrients on growth and yield of 'valencia' sweet orange infected with huanglongbing. HortScience 51:1482–1493. https://doi.org/10.21273/HORTSCI11026-16

Morgan KT, Kadyampakeni DM, Albrigo LG, Boman BJ, Kadyampakeni DK, Vashisth T, Zekri M, Graham J, Johnson E et al (2020) Irrigation Management to Improve Nutrient Uptake, p 65–71. In: Morgan KT, Kadyampakeni DM (eds). Nutrition of Florida citrus trees, Elec. Data Info. Source, SL 462; Univ. of Florida Inst. of Food and Agric. Sci. Gainesville, FL, USA. https://doi.org/10.32473/edis-ss478-2020

Munter RC, Halverson TL, Anderson RD (1984) Quality assurance for plant tissue analysis by ICP-AES. Commun Soil Sci Plant Anal 15:1285–1322. https://doi.org/10.1080/00103628409367559

Naor A (2000) Midday stem water potential as a plant water stress indicator for irrigation scheduling in fruit trees. Acta Hortic 537:447–454. https://doi.org/10.17660/ActaHortic.2000.537.52

Panigrahi P, Srivastava AK (2017) Water and nutrient management effects on water use and yield of drip irrigated citrus in vertisol under a sub-humid region. J Integr Agric 16:1184–1194. https://doi.org/10.1016/S2095-3119(16)61500-9

Reingwirtz I, Uretsky J, Cuneo IF, Knipfer T, Reyes C, Walker MA, McElrone AJ (2021) Inherent and stress-induced responses of fine root morphology and anatomy in commercial grapevine rootstocks with contrasting drought resistance. Plants 10:1121. https://doi.org/10.3390/plants10061121. PMID: 34205907; PMCID: PMC8227383

Sato S, Morgan KT, Ozores-Hampton M, Simonne EH (2009) Spatial and Temporal Distributions in Sandy Soils with Seepage Irrigation : I. Ammonium and Nitrate. 73: https://doi.org/10.2136/sssaj2008.0206

Schmugge TJ, Jackson TJ, McKim HL (1980) Survey of methods for soil moisture determination. Water Resour Res 16:961–979. https://doi.org/10.1029/WR016i006p00961

Scholander PF, Hammel HT, Bradstreet ED, Hemmingsen EA (1965) Sap pressure in vascular plants. Science (1979) 148:339–346. https://doi.org/10.1126/science.148.3668.339

Shahnazari A, Liu F, Andersen MN et al (2007) Effects of partial root-zone drying on yield, tuber size and water use efficiency in potato under field conditions. Field Crops Res 100:117–124. https://doi.org/10.1016/j.fcr.2006.05.010

Suresh K, Tang T, Van Vliet MTH et al (2023) Recent advancement in water quality indicators for eutrophication in global freshwater lakes. Environmental Research Letters, IOP Publishing, 18 063004

Vincent C, Rowland D, Schaffer B et al (2020) Primed acclimation: a physiological process offers a strategy for more resilient and irrigation-efficient crop production. Plant Sci 295

Wells CE, Eissenstat DM (2002) Beyond the roots of young seedlings: the influence of age and order on fine root physiology. J Plant Growth Regul 21:324–334. https://doi.org/10.1007/s00344-003-0011-1

Wells CE, Michael Glenn D, Eissenstat DM (2002) Changes in the risk of fine-root mortality with age: a case study in Peach, Prunus persica (Rosaceae). Am J Bot 89:79–87. https://doi.org/10.3732/ajb.89.1.79