Vol. 13(4), pp. 74-95, October-December 2021
DOI: 10.5897/JHF2021.0676
Article Number: B05293168049
ISSN: 2006-9782
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Journal of Horticulture and Forestry

Review

Regulated deficit irrigation (RDI) under citrus species production: A review

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Received 17 July, 2021; Accepted 23 September, 2021

Regulated deficit irrigation (RDI) is considered among the best water-saving techniques for supplementing Regulated water to fully achieve the water needs of the plant while maximizing water productivity with little or no substantial decrease in final produce compared to the conventional forms of irrigating crops. The aim of this paper is to review existing RDI approaches used in citrus production as well as plant-water stress indicators. Most of the approaches employed in citrus RDI scheduling require weather data for evapotranspiration calculations which is very technical, laborious and time consuming. Nonetheless, the time domain reflectometer (TDR) offers a simple way of scheduling RDI based on the soil-water status at any given time. This approach will help address the challenges in setting up on-farm synoptic stations to measure weather data to compute evapotranspiration or from using data from weather stations which might be different from the farm conditions. The pros and cons of all the approaches have been discussed and recommended that the TDR can be adopted as an alternative to schedule irrigation in citrus orchards to ensure that plants are supplied with adequate volume of water for maximum water use efficiency.

Key words: Partial root-zone drying, plant-water requirement, plant-water stress, regulated deficit irrigation, remote sensing, subsurface irrigation.

INTRODUCTION

Agriculture, considered as one of the principal consumers of water resources uses more than 70% of the global

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freshwater (Dalin et al., 2019; Mekonnen and Gerbens-Leenes, 2020). Climate change, urbanization, industrialization, increasing population coupled with high demand for water for other uses bring about irrigation practices occurring under limited water conditions globally (Al-Ghobari and Dewidar, 2018; Kuscu et al., 2013). Irrigation management will focus on maximizing water productivity (yield produced from water used by crops) compared to productivity per unit area (Fereres and Soriano, 2006). To resolve problems of inadequate water supplies for agriculture, Deficit Irrigation (DI) as a management tool should be encouraged to realize the objective of reducing irrigation water use while maintaining or maximizing farmers profit without essentially varying the production area (Fereres et al., 2003; Rosa et al., 2020). Hence, adopting sustainable irrigation practices to ensure maximum efficient water usage efficiency is very important (García-Tejero et al., 2011a). Several studies suggest a shift in the assessment of effectiveness of irrigation schemes from yield per unit acreage to yield per unit water used up (Fereres and Soriano, 2007; Romero et al., 2006). Through effective irrigation, crop vegetative and reproductive development can be effectively managed. Irrigation operators are progressively exploring new ways to improve the WUE of crops through better irrigation management practices. Underpinning new irrigation techniques is an understanding of the associated physiological responses which predicts plant stimulus and support in exploring minimum water needs for economically viable returns (Bacon, 2004).

Deficit irrigation (DI) involves all farm activities aimed at supplying the plant with a volume of irrigation dose lower than the plant's maximum water needs. In conditions where water availability is limited, DI has been extensively proven to be practicable by increasing water productivity while maintaining or improving plant yield (García-Tejero et al., 2011b; Zou et al., 2021).

In highly-dense orchard plants like apples, peaches, and avocados, where the ratio between asexual and sexual reproduction development is crucial, regulated deficit irrigation (RDI) has been used (Blanco et al., 2019; Vélez-Sánchez et al., 2021). The basic principle of RDI is to withhold irrigation water in the highly vegetative growing stages while fruit development or grain filling is minimum (Blanco et al., 2019; Lurbe, 2013). Normal irrigation regimes are restarted in the future when there is quick fruit development after the water restrictions. The main essence of water deficit is yield optimization per unit volume of irrigation water applied (Fernandes-Silva et al., 2018; Faghih et al., 2019; Blanco et al., 2020). Maximum profit may be achieved by reducing irrigation water used and costs through DI (Trout and Manning, 2019). This study aimed at reviewing existing RDI approaches used in citrus production. Most studies show that RDI schedules in citrus are mainly based on citrus evapotranspiration needs rather than considering the prevailing soil moisture content at any given time. Nonetheless, water availability for plant optimum growth is determined by several factors including soil, weather, plant and other environmental conditions (de Jong van Lier, 2014). Hence, there is the need to seek alternative irrigation management techniques not solely dependent based on the plant's full crop water requirements (ETc) replacement but rather the prevailing soil water conditions.

DEFICIT IRRIGATION

Definition and approaches to DI in citrus

DI is defined as any agronomic water management system or irrigation practice whereby plants are supplied with volumes of irrigation water below the full plant-water requirement or evapotranspiration needs provided by stored soil water, rainfall, and irrigation for optimum plant growth throughout the entire farming period (Chai et al., 2016). The principal idea underlying this method basically is by reducing the amount of irrigation water applied, positively enhance the crop's stimulus towards an appreciable water stress level, increase the crop WUE and further reduce the volumes of water applied on the field (García-Tejero et al., 2011a; Tabatabaei et al., 2017). Even though there are no standardized water-stress levels assigned to plant-water relations, Chai et al. (2016) classified plant-water stress level using these following water content of the soil at field capacity as shown in Table 1.

Forms of RDI under citrus cultivation

Recently, water saving techniques like RDI has been adopted in most citrus growing orchards. RDI is mostly implemented on the field in the form of either growth stage-based DI or partial root-zone drying DI (Chai et al., 2016; Kadyampakeni et al., 2018). Table 2 shows the main approaches to RDI, their advantages, disadvantages and period of water application.

CITRUS IRRIGATION

Water scarcity in citrus production

Water availability is essential for crop production. Wright (2000) reported that mature citrus trees use about 64 and 511 L of water daily in winter and summer, respectively. Swain (2012) also indicated that matured citrus plant utilize more than 190 L of water in a day. These clearly

Table 1. Classifying plant-water stress based on available soil water at field capacity.

Plant-water stress status	Description based on available soil water at field capacity (% FC)
Over-irrigation	High volumes of water (> 100%) given to the plant exceeding the evapotranspiration needs for ideal plant growth.
No deficit or full irrigation	Readily available soil moisture content for plant is above 70% of the field capacity during the main developmental stages of plant.
Mild water deficit	Readily available soil moisture content for plant is between 60 to 70% of the field capacity.
Moderate water deficit	Remaining readily available soil moisture content for plant use is between 50 to 60% of the field capacity.
Severe water deficit	Readily available soil moisture content for plant use is less than 50% of the field capacity.

Table 2. Approaches to RDI used in citrus cultivation.

Approach to RDI	Period of water application	Advantages	Disadvantages
Growth stage-based deficit Irrigation is a form of RDI where irrigation water is given at different stages of the plant especially at the crucial developmental stages while reducing irrigation water at the non-crucial developmental phases (Chai et al., 2016).	Crucial periods like flowering, fruiting, and maturity.	1. No significant reduction in plant productivity or yield (Faghih et al., 2019; Blanco et al., 2020).	Reduced crop development (Faghih et al., 2019; Blanco et al., 2020).
Partial root-zone drying (PRD) is a form of RDI where the soil around the plant's root zone is watered and allowed to dry simultaneously. Portions of the root area are irrigated to the full volume of water required leaving the remaining area without any supply of water (Ahmadi et al., 2011; Chai et al., 2016; Wu et al., 2020).	Water can be applied at any given time in the development stage of the plant.	1. Easy to regulate the time to apply water deficit. 2. Easy to control vegetative and reproductive processes.	1. Reduction in biomass production. 2. Improper irrigation schedules can cause salinity problems when the dry phase exceeds the normal time of research (Iqbal et al., 2020).

show that citrus trees require much water for development and optimal production. Nonetheless, the increasing demand for water for domestic, industrial and other commercial purposes poses serious threat to the availability of water for agriculture. This predicts a great decrease regarding the availability of water resources needed for irrigating crops for increased food security globally and hence the necessity to improve on irrigation approaches which permit farmers to use less water with the minimum possible effect on yield. Insufficient water supply has several effects on citrus crop production such as peel cracking, reduced fruit size and quality, reduced titratable acids and lower economic returns for the farmer (Saitta et al., 2021).

Citrus crop critical periods

In citrus, the flowering stage is considered very critical and hence moderate water stress during this phenological period may reduce the number of fertilized ovules and an increase in fruit drop (June fruit drop) reduced number of fruits and subsequently compromising, yield (García-Tejero et al., 2010; Saitta et al., 2021). Other phases in fruit development are similarly regarded as extremely critical to deficit irrigation. Additional water stress on citrus trees in last stage of fruit development and ripening may lead to a decrease in produce resulting from the decreases in fruit sizes as well as peel creasing and cracking (González-Altozano and Castel, 1999; Pérez-Pérez et al., 2009; García-Tejero et al., 2010; Li and Chen, 2017; Saitta et al., 2021). The most suitable time to apply water stress in citrus is the time following “June fruit-drop”. This is because at the end of water deficit, fruits can grow faster when irrigation is brought back to the initial volume applied than those fruits under normal irrigation conditions (Mitchel and Chalmers, 1982; Chalmers, 1986; González-Altozano and Castel, 1999). Cohen and Goell (1988) and González-Altozano and Castel (2000) further indicated that deficit irrigation inhibited fruit development in terms of size though there was continuous accumulation of dry matter but after irrigation was restored, a counter-balance of fruit development ensued permitting fruits to grow quicker compared to fruits on the well-irrigated plants, and consequently attaining the same final size. Once RDI approaches are used during summer, there is the need to return irrigation volume to original volume (dose) satisfactorily prior to harvesting so as to permit a probable compensatory fruit growth. In July-August, when ‘Clementina de Nules’ in Valencia were subjected to moderate water-stress (that is irrigating up to only 50% of full ETc.), there was no substantial reduction in yield and fruit size. However, when citrus trees were severely water-stressed during summer there was reduced tree development and final fruit size but the total soluble solids increased (González-Altozano and Castel, 1999).

Effects of deficit irrigation on citrus yield

In fruit crops the main effect of DI is decreased vegetative growth (Lurbe, 2013; Blanco et al., 2020), affecting mostly the extension of sprouts and new branches (Hsiao, 1973, 1993; Lurbe, 2013). According to Hsiao et al. (1976) and Lisar et al. (2012), this decrease in foliage growth is an adaptive mechanism to plant-water stress because less plant foliage leads to low plant radiation interception and subsequently a decrease in water loss by transpiration. Wright (2000) also observed rolling-up of the outer canopy of citrus trees when subjected to moderately-to-severe water-stressed environments in order to minimize solar radiation interception. Reduced growth is observed in the main trunks and branches of deficit irrigated trees resulting to smaller canopy sized trees. Subjecting lemons however, to reasonable water restriction did not reduce branch or sprout development (Domingo, 1994; Lurbe, 2013). Some studies have recorded decreased root growth as an effect of DI on plant roots resulting from less available soil-water (Landsberg and Jones, 1981; Bevington and Castle, 1985; Lurbe, 2013). Kramer and Boyer (1995), however, argued that this growth reduction at the root zone is generally lower than what is observed in the aerial plant parts leading to an increase in the root-to-shoot ratio leading to an adequate water delivery to the leaves and fruits (Syvertsen, 1985; Lurbe, 2013). Crop sensitivity to a period of water restriction is a variable of the duration and intensity of the water deficit regimes (Fereres and Soriano, 2007). Managing water stress effectively is important for a successful RDI application: in the absence of accurate and reasonable water stress parameters, RDI might not be appropriate. This is because plant responsiveness to a certain water stress condition compared to the possible evapotranspiration may lead to varied degrees of crop water stress depending on the soil, environment and plant endogenic characteristics. Exceeding the maximum plant water stress value generally decreases the ultimate fruit size and farm financial returns. It is therefore prudent that when applying RDI strategies, one must regularly monitor the level of plant water in order not to exceed the acceptable documented values for various plant species (Lurbe, 2013).

CITRUS PLANT-WATER STRESS INDICATORS

García-Orellana et al. (2007) and González-Dugo et al. (2012) suggested the usage of plant-based parameters to monitor the crop water condition to know if plants have attained the required state of stress before the application of any successful RDI strategies. The most frequently used methods to study the water condition in fruit trees and other woody-plants are to measure the stem-water potential and stomatal conductance (Fernández, 2017). These approaches may be time-consuming, arduous, and requires manual operations (Romero-Trigueros et al., 2019). Lurbe (2013) emphasized that due to the challenges posed by these ‘classical’ approaches in detecting plant-water stress conditions, there is need to research into alternative ways which will do away with the challenges caused during the use of these ‘classical’ methods stated earlier.

Stem water potential (Ψs)

The most widely used approach in studying the plant-

Figure 1. Pressure chamber for measuring stem and leaf water potential.
Source: https://edaphic.com.au/plant-and-leaf-water-potential/water-potential-pressure-chamber-standard/

water relations in fruit trees is to measure the stem-water potential (*Ψs*) with the pressure chamber (Scholander et al., 1965; Levin, 2019). *Ψs* is considered to be very responsive to high irrigation stress compared to leaf water potential owing to its accuracy in determining crop water stress in some types of fruit trees species owing to the rapid response to irrigation schedules (Garnier and Berger, 1985; Naor, 2000, 2004). *Ψs* measures the potential energy which the vascular bundles use to retain water within the xylem tissues. Conventionally, plants grown in less humid soils tend to exhibit lower *Ψs* compared to well-watered plants (González-Dugo et al., 2012). Environmental or endogenous factors, non-automation, laborious measurement coupled with low water availability are some of the disadvantages of using stem water potential in monitoring citrus water conditions (Lurbe, 2013; Romero-Trigueros et al., 2019). Figure 1 shows a picture of a Pressure chamber.

Stomatal conductance (*gs*)

Though laborious when used to determine plant water stress, *gs* measurement shows an advantage over *Ψs* because of its non-destructive nature hence measurements can be done several times on the same leaves of one specific tree. Similar to *Ψs*, *gs* is very responsive to less available soil water making less watered tress to generally possess less *gs* values compared to trees that are irrigated. Citrus trees are considered mesophytes with leaves exhibiting xeromorphic characteristics with most of the stomata found underside of the leaves whereas the upper surface is overlaid with thick waxlike cuticle that subdues cuticular transpiration (Spiegel-Roy and Goldschmidt, 1996; Carr, 2014). This makes citrus leaves to have lesser *gs* values compared with trees like almond, persimmon, or pistachio in similar soil-water environments. Measurement of *gs* depends on prevailing soil-moisture content, solar radiation, temperature, air vapor-pressure deficit (VPD), leave age, etc. (Jones, 1983). Oguntunde et al. (2007) and Villalobos et al. (2009) recounted that VPD plays an essential role in regulating transpiration in well-irrigated citrus plants hence citrus have reduced *gs* values in response to high VPD. Figure 2 shows the use of a potable Porometer to measure stomatal conductance in a leaf.

Sap flow

Measuring of sap flow is vital for studying plant-water

Figure 2. Porometer for measuring leaf stomatal conductance.
Source: www.delta-t.co.uk

relations in properly irrigated as well as highly stressed plants because it provides an exact approximation of water flow in plants (Smith and Allen, 1996). Several procedures are employed to measure sap flow in trees based on various approaches but the frequently used methods are by the use of heat pulse to trace sap flow (Čermák et al., 2004) and it has worked for several years (Lurbe, 2013). Some new methods formulated to quantify sap flow under varied experimental conditions include the Trunk-Sector Heat Balance (THB), Heat Dissipation (HD), Stem Heat Balance (SHB), Green's Heat Pulse Velocity (HPV), Calibrated-Average-Gradient methods (CAG), among others (Testi and Villalobos, 2009; Fernández et al., (2008); Lurbe, 2013). Most citrus RDI trials performed have calculated water savings gained as the basis of water applied but not emphasizing the exact approximation of tree transpiration. Transpiration in plants is dependent on both available soil water as well as evaporation needs. Valancogne et al. (1997) and Fernández et al. (2008) in the last few decades have described relative transpiration (that is, the fraction of sap flow in highly stressed and highly irrigated trees) as a water-stress parameter. Furthermore, additional indicators obtained during sap flow experiments might be used to identify water stress. In highly stressed olive trees, Fernández et al. (2001) and Nadezhdina et al. (2007) observed a slight transformation in the sap-velocity profile nearer to the cambium compared with highly irrigated trees. The authors proposed the likelihood of employing the sap flow ratio in the inner/outer xylem regions as a water stress parameter which could be used in automated irrigation-control systems. López-Bernal et al. (2010) found than in olive trees, there was a rise in the night-to-day sap flow ratio (N/D index) when the soil dried up signifying that the N/D index may be good water stress indicator. Figure 3 shows how the SFM1 Sap flow meter is used to measure transpiration or sap flow in plants.

Canopy temperature (Tc)

Plants in soil water-stressed conditions often have reduced stomatal conductance, thus minimizing the transpiration rate and hence an increase in leaf temperature. A very good plant-water stress parameter is obtained through estimating the ultraviolet radiations emanating from the tree cover (Jones, 1999; Merlot et al., 2002; Jones et al., 2002). Jones et al. (2009) observed that stomatal openings may be affected by several factors including highly water stressed soil, endogenous tree factors, biotic conditions (e.g. pests and diseases) as well as other environmental conditions like emerging radiation, air temperature, and wind. Additionally, tree morphology (that is canopy shape and leaf size) and other mechanisms regulating plant transpiration can directly affect canopy temperature (Scherrer et al., 2011). Another technique for measuring the Tc is via thermal remote sensing. Thermal remote sensing could be applied to measure a wider crop coverage particularly through thermal imaging (Jones, 2004; Drechsler et al., 2019). Thermographic cameras mounted on airborne platforms or hand-operated cameras mounted on tripods

Figure 3. SFM1 Sap flow meter to measure transpiration or sap flow in plants.
Source: www.ictinternational.com

Figure 4. A thermal infrared thermometer in use.
Source: https://edaphic.com.au/temperature/infrared-temperature-sensor/

platforms, or cranes may be used to acquire images (Möller et al., 2007; Berni et al., 2009; Romero-Trigueros et al., 2019) as seen in Figure 4. Several images can be acquired through automation to determine the mean Tc of (Fernández, 2017) and speeded with methods similar to what before the reference (Fernandez, 2017 ; Jiménez-Bello et al. (2011) established for subsequently analyzing the images acquired, allowing the images obtained from each tree to be analyzed in the absence of the operator, thereby reducing time wastage

(about 16 min/image) compared to the manual method. Fuchs (1990) and González-Dugo et al. (2012) also suggested that the intra-crown standard deviation measurement can indicate the presence of water shortage in plants. González-Dugo et al. (2012) found in almonds an increasing variability of Tc in fully irrigated trees while Tc variability diminished when there was mild to severe water-stress. Intra-canopy variations in Tc, every single tree for analysis from a single operator however, did not affect water status in other woody plants like grapevines (Grant et al., 2007; Möller et al., 2007). Hence, further research should be conducted in different tree crops to assess the possibility of making intra-canopy Tc variations a good parameter to monitor plant-water conditions.

Remote sensing in water stress detection

Recently remote sensing is used to study crop drought, the dangers arising from forest and grassland fires, crop cultivation as well as changes in land-usage (Zhang et al., 2010). Through remote sensing, spatial and spectral imagery data can be obtained and characterized for drought, diseases in crops and insect invasion at diverse temporal resolutions (Lan et al., 2017). Vegetation water content estimated through remote sensing techniques can offer significant inferences on the vegetation's physiological state (Peñuelas et al., 1994; Yi et al., 2013), decision in agricultural irrigation practices (Zhang et al., 2012; Yi et al., 2013, 2014), and assessment on plant-drought conditions (Cohen, 1991; Mirzaie et al., 2014). Moreover, remote sensing may be successfully used when characterizing vegetation water status, precisely reflecting the physiology of that vegetation experiencing high stress, quickly identifying water scarcity while instantly adopting good irrigation practices (Zhang et al., 2012; Yi et al., 2014; Cao et al., 2015). Sullivan et al. (2007) studied the response of cotton to water deficit and crop residue management by using a cheap unmanned aerial vehicle (UAV) fitted with a thermal infrared sensor which showed that thermal infrared emittance showed a positive responsiveness to canopy response in relation to measurements from ground tools and hence suggested that images acquired by thermal infrared at low-altitude UAV can be employed to control within-season canopy stress.

Remote sensing practices have successfully been used to study vegetation water conditions or crop water stress on a dynamic multi-scale and instantaneous observation; however, there are different views on the most appropriate technique among the water content indicators to employ to remotely study crop water stress levels. The main strengths and weaknesses of the procedures used to study plant-water status are presented in Table 3 below.

CITRUS WATER REQUIREMENTS

Calculating citrus water requirements

Doorenbos and Pruitt (1977) and Allen et al. (1998) estimated citrus water requirements (ET_c) as follows:

$$ET_c = ET_o \times K_c \quad (1)$$

where ET_o = reference evapotranspiration, K_c = the crop coefficient.

ET_o is the rate at which "an extensive surface of green, well-watered grass of uniform height, actively growing and completely shading the ground evaporates water" (FAO-56 method). The values of ET_o are depended on the prevailing climatic conditions of the study area and can be estimated by other approaches from available climatological data, with the FAO-Penman-Monteith method being the most commonly used (Allen et al., 1998).

K_c = the crop coefficient (the ratio between ET_c and ET_o) which differs with the definite crop features: type of plant, developmental period, plant size, and farm routines as well as loss of water from the soil).

Some experiments reported single annual K_c values for citrus trees (Grieve, 1989; Grismer, 2000), however, different experiments have proven that within a given growing season K_c values can vary. Castel et al. (1987) and Castel (1997) in Valencia showed varying K_c seasonal values when determining the monthly K_c values in both surface irrigated matured orange plantations as well as a drip-irrigated 'Clementina de Nules' tree planted in an accurate weighing lysimeter. Villalobos et al. (2009) explained that the differences in the results obtained by Castel and other related studies were as a result of the changes in soil evaporation situations and canopy ground cover ratio (GC) of crops, hence the necessity to measure transpiration and soil evaporation separately. Villalobos et al. (2009) subsequently proposed using transpiration models in calculating K_c values as a function of specific variables to minimize the repetition of experiments in diverse environments. Villalobos et al. (2009) then developed a direct connection for the citrus transpiration coefficient (K_p) and GC (from less than 0.01 to almost 0.80) that could also calculate citrus transpiration as:

$$T = K_p \times ET_o = 0.65 \times GC \times ET_o \quad (2)$$

However, Castel (2000) in his work, related K_c and GC, using a quadratic equation as:

$$K_c = 0.0283 + 0.0203\, GC - 0.00016 GC^2 \quad (3)$$

Scheduling regulated deficit irrigation based on continuous monitoring of soil-water content within the soil profile

An alternative to applying RDI treatments is by the continuously the plant-water status using a soil moisture sensor (e.g., Time-Domain Reflectometer (TDR) and Frequency Domain Reflectometer (FDR)). The TDR/FDR

Table 3. Main strengths and weaknesses of procedures used to study plant-water status.

Procedures	Explanation	Strengths	Weaknesses
1. Soil water measurement			
(a) Gravimetric method	Soil sample is weighed, oven-dried and re-weighed to determine the volume of water given out from the plant-soil continuum.	-Consistent -Direct source of data for soil-moisture conditions. -Basic guide to the volume of irrigation water needed when scheduling irrigation.	Laborious, damaging, and time-intensive.
(b) Soil moisture sensors (I) Neutron probe	Fast energy neutrons (^{1}n) from a radioactive source are released into the soil.	Rapid, portable, largely automated, non-destructive, and repetitive.	-Radioactive in nature and requires appropriate technical, operation, storage, and inspection. -Only suitable for field operations. -Calibration is site specific.
(II) Time Domain Reflectometer and Frequency Domain Reflectometer	Working principle depends on the disparity in the dielectric constant of water and soil.	-Accurate application on the field. -Simple and automated for continuous soil-water measurements. -No radiation hazards.	-Require several sensors for a larger field. -Expensive in repairing and installing sensors.
(III) Tensiometers	This is used to measure the soil-water potential.	Simple for scheduling water application.	-Convenient in coarse-textured soils. -Cannot be applied in broad array of soil moisture conditions.
2. Soil-water balance method	Indirectly estimates soil moisture level from soil-water balance estimations.	Easy and useful criteria to determine how much irrigation water to supply.	-Less reliable and must be rectified with established soil measurements. -Needs an estimation of evaporation, rainfall, as well as irrigation events.
3. Plant-based methods			
(a) Stomatal conductance	Estimates tree water level by measuring stomata openings.	-Useful tool for monitoring tree-water level. -Useful for standardizing several experiments.	-Laborious and cannot be automated for commercial applications. -Unsuitable for anisohydric crops.
(b) Leaf water potential	Directly measures leaf water content.	Extensively recognized reference technique.	Sluggish, damaging, and not suitable for isohydric crops.

Table 3. ContD.

(c) Relative leaf water content	Directly measures water levels in leaves.	Good estimator of plant water conditions and does not need complex instruments.	Damaging and time-intensive.
(d) Sap flow measurement	Estimates transpiration rate by means of heat pulse.	-Subtly responds to stomatal closure and water stress. -Can be modified for automatic recording and monitoring of irrigation setups.	-Needs to calibrate individual plants. -Needs complex device and skills.
(e) Stem and fruit diameter	Measures variations in stem and fruit diameters as feedback to the fluctuations in available water.	Sensitive measure of tree water deficit.	Unsuitable for regulating high-frequency irrigation setups.
4. Remote sensing methods			
(a) Infrared thermometry	Estimates canopy temperature, which increases as a result of water stress.	Consistent and not destructive.	-Depends on just limited point measurements. -Soil and tree heterogeneity are not considered.
(I) Crop Water Stress Index	Adopts the changes in canopy as well as air temperatures to measure crop water stress.	Susceptible to closing of stomata and crop water deficit.	Affected by the cloud cover; needs separate baseline equations for dissimilar crops.
(II) Degrees Above Non-Stressed (DANS), Degrees Above Canopy Threshold (DACT), and Canopy Temperature (Tc) ratio	Estimates single canopy temperature for calculating water stress.	-Require less data than CWSI to detect water stress. -Tc ratio provides quantitative water stress coefficient (Ks) for estimating crop evapo-transpiration.	Difficulty in scaling up for vast cropped farmlands.
(b) Spectral vegetation indices			
(I) Structural indices	This estimates reflectance indices within the visible spectrum and near infrared regions (Normalized Difference Vegetation Index, Renormalized Difference Vegetation Index, Optimized Soil-Adjusted Vegetation Index, Transformed Chlorophyll Absorption Ratio Index) to show canopy variations from insufficient supply of water.	Not destructive with high temporal and spectral resolution.	-Difficulty in analyzing images obtained. -Accuracy is decreased from leaf level to canopy level.

Table 3. ContD.

(II) Xanthophyll indices	These estimate Photochemical Reflective Index and Normalized Photochemical Reflective Index, which are responsive to the cycle of converting xanthophyll pigments into epoxidates.	Responsible for changes in physiology in the photosynthetic pigment resulting from water deficit.	Tedious in converting raw images to comprehensible irrigation applications.
(III) Water indices	Estimates the reflectance trough in the near-infrared range (Water Index, Simple Ratio Water Index, and Normalized Difference Water Index) to indicate canopy water status.	Quick and not destructive estimation of leaf water content.	Difficulty in scaling up to the canopy level.

Source: Ihuoma (2020).

readings measure the prevailing soil-water condition as a percentage volume of soil water content at field capacity. The TDR measures soil water indirectly by converting the travel time taken by electromagnetic waves (electronic pulse) in a waveguide (probe) sent into a porous medium (soil) for which the volumetric water content (θ_v) estimate is needed. The soil θ_v is then determined from the dielectric constant, *k* of the soil (Evett and Heng, 2008; Abdullah et al., 2018). The dielectric constant, *k,* has a minimum value of 1 in vacuum and 80 as in water which makes it highly possible for its use to measure θ_v. The velocity at which the electromagnetic wave moves along the conductors and through the soil is reduced as the dielectric constant, *k*, of the soil becomes high. Hence, increasing the water content increases the soil's dielectric constant, *k*, and subsequently increases the travel time of the electromagnetic wave (Abdullah et al., 2018).

The automation, accuracy, ease of use and non-destructive nature of the TDR in measuring θ_v makes it a useful tool to monitor soil moisture content (Ihuoma, 2020). The TDR has been successfully used in potted experiments to monitor soil water content. Alordzinu et al. (2021) used the TDR (IMKO® Trime-Pico HD2 64) to successfully monitor and schedule irrigation in tomato grown in pots under greenhouse conditions. Additionally, Schumann and Waldo (2017) successfully used the TDR (Acclima®) to monitor the soil water content and schedule irrigation in hydroponically potted Tango citrus trees in Lake Wales, Florida as seen in Figure 5 below.

Measuring soil water content with the TDR/FDR shows a strong correlation with the values obtained when the gravimetric method of measuring the θ_v is used. This makes the use of these devices an option that can be used alone when measuring soil water content both in the laboratory and the field. Previous studies have shown strong correlation values (R^2) above 0.85 for TDR/FDR soil-water measurements and gravimetric method shown in Table 4.

Notwithstanding the pros of using the TDR, the TDR has a few setbacks including high cost of purchasing, repairing and installing of sensors to cater for larger fields. Furthermore, TDR accuracy reduces in soils with high water content (Abdullah et al., 2018).

In scheduling irrigation with the TDR, first irrigate all the plants with equal volumes of water and allow them to stay within the soil for some time interval (depletion time). Monitor and estimate the reduction in field capacity (FC) and manageable allowable depletion (MAD) status of the soil using the TDR. The final soil moisture content at wilting point is determined using the TDR and compared with the initial field capacity determined, find a relationship between the initial estimated FC and TDR readings. The difference in water estimated in the laboratory using the gravimetric method. Based on the differences determined, find a relationship between the initial estimated FC and TDR readings. The difference

Figure 5. Acclima® TDR Soil-Water sensor installed in pots for hydroponically grown Citrus under protective screen in Lake Wales, Florida.
Source: Schumann and Waldo (2017).

Table 4. Summary of the correlation between Time Domain Reflectometer/Frequency Domain Reflectometer and gravimetric method.

Research	Correlation coefficient (R^2)	Author(s)
“Using plant water status to define threshold values for irrigation management of vegetable crops using soil moisture sensors”	$R^2 = 0.88$	Thompson et al. (2007).
“Soil moisture estimation using gravimetric technique and FDR probe technique: A comparative analysis”.	$R^2 = 1.00$	Shukla et al. (2014).
“A comparison of the gravimetric and TDR methods in terms of determining the soil water content of the corn plant”.	$R^2 = 0.91$	Tanriverdi et al. (2016).
“Mandarin irrigation scheduling by means of FDR soil moisture monitoring”.	$R^2 = 0.90$	Martínez-Gimeno et al. (2020).

in water amount obtained will be supplied to the soil to maintain its FC for optimum plant use. Hence, the plant is irrigated with the volume of water used up anytime the TDR readings show a reduction in the available volume of soil water at any particular time.

CONCLUSION

This review highlighted the feasibility of using the TDR as another alternative to schedule RDI in citrus by monitoring the prevailing moisture content of the soil rather than the evapotranspiration needs of citrus. Since availability of fresh water for agriculture is increasingly becoming scarce, it is prudent to adopt this approach of implementing RDI in order to ensure the sustainability of citrus production by optimizing water use efficiency.

CONFLICT OF INTERESTS

The authors have not declared any conflict of interests.

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