Europ. J. Agronomy xxx (2016) xxx–xxx

Contents lists available at ScienceDirect

European Journal of Agronomy

journal homepage: www.elsevier.com/locate/eja

Partial root-zone drying irrigation in orange orchards: Effects on water use and crop production characteristics

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ARTICLE INFO

Article history:
Received 21 March 2016
Received in revised form 27 October 2016
Accepted 1 November 2016
Available online xxx

Keywords:
Citrus
Deficit irrigation
Plant physiology
Sap flow
Sustainable water management

ABSTRACT

We have studied the effects of partial root-zone drying (PRD) on plant physiological response, plant-soil water dynamics, yield and fruit quality of young orange trees during the irrigation seasons 2013 and 2014 in an orchard located in Eastern Sicily (Southern Italy). The irrigation treatments included: (i) full irrigation (T1), with trees irrigated by supplying 100% of crop water demand using micro-irrigation systems; and (ii) alternate partial root-zone drying (T4), with trees irrigated at 50% of crop water demand. Minimally invasive electrical resistivity tomography (ERT) was adopted to help quantify root-water-uptake (RWU) processes at the finer (decimetric) spatial scale. Results show that, compared with the full irrigation treatment, PRD at 50% of crop water demand (ET_c) increased the fruit yield by 20% in 2013 and 10% in 2014. The PRD irrigation treatment, which induces a reduction of the wetted soil volumes, had also obvious positive effects on water use efficiency (WUE), compared to full irrigation. From the results of this study, we concluded that when water resources are limited, PRD at 50% level of ET_c is an efficient water saving strategy to increase WUE, while other physiological and growth parameters are practically unaffected.

1. Introduction

According to FAO (2011), between now and 2050, the world's population will increase by one-third and agricultural production will have to increase still by 60% to satisfy the expected demands for food. Climate change will make this task even more difficult under a business-as-usual scenario, due to adverse impacts on agriculture, requiring spiralling adaptation and related costs. The most immediate impact of climate change on water for agriculture is through the increased variability of rainfall, higher temperatures, and associated extreme weather events, such as droughts and floods. In the medium to long term, climate change will affect water resources and reduce the availability or reliability of water supplies in many areas already subject to water scarcity. As agriculture is the main user of freshwater resources worldwide, we expect that the main impact of climate change on agriculture will be via water. At the same time, competition for water use is also likely to carry the main impact of other stressors linked to development (Tilman et al., 2002).

To address these intertwined challenges, agricultural systems have to become, at the same time, more efficient and resilient, at every scale from the farm to the global level. These systems have to become more efficient in resource use (use less land, water, and inputs to produce more food sustainably) and at the same time become more resilient to changes and shocks (Hsiao et al., 2007).

Citrus are commercially grown in about 80 countries in the world (FAO, 2013) and the major growing regions include arid and semi-arid areas of the Mediterranean basin such as Spain, Italy, Greece, Egypt, Turkey and Morocco (Romero-Conde et al., 2014). In these areas, since annual rainfall is generally lower than crop water demands, or rainfall temporal distribution does not satisfy seasonal demands during fruit growth, citrus yields heavily depend on irrigation. Citrus in fact is an evergreen plant requiring water all year round and there are times when water stress can trigger physiological responses that allow the plant to cope satisfactorily with reduced water availability (Hutton et al., 2007). Citrus irrigation studies (Bevington et al., 1996; Hutton et al., 2007) showed that significant water savings may be achieved by intensifying the irrigation intervals whilst simultaneously controlling the depth of wetted soil during the fruit development stage, but at the cost of a reduction in fruit size, even though total fruit yields are unaffected.

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http://dx.doi.org/10.1016/j.eja.2016.11.001
1161-0301/

The application of water to only a part of a plant's root system is now common practice in fruit production areas throughout the world (e.g. de Lima et al., 2015). Partial root-zone drying (PRD) has been reported to be a promising technique to increase water use efficiency (WUE) with no decrease in crop productivity (Loveys et al., 1997; Kang et al., 2003; Fernández et al., 2007; Hutton and Loveys, 2011; Ballester et al., 2013; Consoli et al., 2014; Parvizi et al., 2014, 2016).

PRD is a strategy based on the periodic irrigation of half of the root system, while the other half is left under dry soil. The wetted and dried sides of the root system are alternated on a time cycle according to the type of crop, its growing stages and existing soil water content (Zhang et al., 2001; Capra et al., 2008; Romero-Conde et al., 2014; Consoli et al., 2014). This strategy is based on the theoretical assumption that the irrigated root half would maintain the water status of the plant, whereas the non-irrigated half would send chemical signals to the shoots via the xylem water in order to reduce stomatal conductance, and thus the relevant water demand.

The physiological mechanisms behind PRD may be able to reduce irrigation water use, thus decrease canopy vigour and yet maintain crop yield, when compared with conventional irrigation methods (Intrigliolo and Castel, 2009; Kang et al., 2000; Hutton and Loveys, 2011; Consoli et al., 2014). Water use efficiency is thus improved. PRD has successfully been used in grapevine (De la Hera et al., 2007), pear (Kang et al., 2002), peach (Goldhammer et al., 2001), olive (Fernández et al., 2006) and apple (Talluto et al., 2008) crops. However, the technique has been scarcely studied in citrus (Melgar et al., 2010): overall, few details are available about the soil water distribution, citrus growth response to PRD, and on its effect on citrus plant physiological processes.

Among the available studies on PRD, Poni et al. (1992) found that the water requirements in the studied orchards could be satisfied by supplying water to only half of the root-zone. Intrigliolo and Castel (2009) indicated the difficulty of successfully employing the PRD for grape with a drip system in heavy and deep soil. Kang et al. (2003) suggested that PRD enhances the hydraulic conductance of tree roots, and the roots have a greater water uptake capacity than in conventional flooded irrigation, given the same average soil water content in the root-zone. Studies have also showed that the application of PRD resulted in stomatal closure compared to a fully irrigated treatment, with the stomatal conductance decrease being related to the plant's sensitivity to drought and to the intensity of water stress (Davies et al., 2002).

Maintaining high irrigation efficiency, i.e. optimizing the match between the applied water and the actual crop water needs, is an important goal, as water resources are limited, but also in view of mitigating the negative environmental impacts of irrigated agriculture, such as the potential threats to groundwater caused by excessive leaching of nitrates (e.g. Dahan et al., 2014).

However, the mere adoption of localized irrigation strategies (such as drip irrigation) does not guarantee high irrigation efficiency, as there are many design and management factors that, for instance affect drip irrigation performance. In a recent study, Phogat et al. (2014) showed that around 34% of the applied water drained out of the root-zone, despite the fact that irrigation needs were based on precise estimates of crop evapotranspiration. This is clearly due to small scale infiltration processes that cannot be identified from large scale estimates. In turn, this fact shows the importance of combining monitoring of soil water dynamics with identification of root-soil interactions, in order to support choices related to irrigation strategies (e.g. Cassiani et al., 2015; Satriani et al., 2015; Consoli et al., 2016). For soil moisture estimation, geophysical imaging obtained from electrical resistivity tomography (ERT) is a very attractive tool (e.g. Cassiani et al., 2015, 2016), at scales ranging from the meter to the decimetre scales, or finer. The application of these time-lapse (i.e. geophysical methods provide information with high spatial and temporal detail about the soil structure and the soil water dynamics, and this allows monitoring water losses for percolation into the deeper layers, beyond the root zone.

The objective of this work is to study the effects of water stress associated with PRD on physiological responses, water exchanges in the soil-plant system, crop yield and quality of orange trees in a citrus orchard located in Eastern Sicily.

2. Materials and methods

2.1. Site description, climatic data and crop evapotranspiration estimates

The study site is an orchard with orange (*Citrus sinensis* (L.) Osbeck), in Eastern Sicily (Italy) (latitude 37°20′ N, longitude14°53′ E), with six-year old trees planted at a spacing of 6 m by 4 m, and an area pertaining to each tree of 24 m^2. The experiments related to the irrigation seasons between June and October in 2013 and 2014. The experimental area belongs to the National Citrus and Mediterranean Crops Research Centre (CREA). The climate of the region is semiarid Mediterranean, with hot and dry summers. Annual mean reference evapotranspiration and rainfall are about 1500 mm and 500 mm, respectively (Figs. 1 and 2). The maximum temperature in summer during daytime often reaches 38–40° Celsius. The mean daily relative humidity (RH, %) was 67% (±13%). The mean daily reference evapotranspiration for the study period (June–October 2013 and 2014) was about 4.0 (±2.2) mm d^{-1}. The weather conditions prevailing at the experimental site (global radiation, relative humidity, wind speed and direction, air temperature) were logged hourly during the experiments using an automatic weather station surrounded by grass. The data were used to calculate daily reference evapotranspiration (ET_0) using the classical Penman-Monteith equation (Allen et al., 1998, 2006).

Crop evapotranspiration (ET_c) was estimated by multiplying daily reference evapotranspiration (ET_0), by the seasonal crop coefficient for orange orchard (K_c) (Allen et al., 1998). The K_c was of 0.7, according to an average canopy ground cover of about 60% (Consoli et al., 2006). A further correction coefficient (K_r) was applied to account for the smaller tree size (Fereres et al., 1981).

K_r was assumed equal to 0.68. The same values of K_c and K_r were used during the two experimental seasons.

The soil at the experimental field has a sandy-loam texture (69.7% sand, 10.5% clay, 19.8% silt), with a percentage of organic matter equal to about 1.25%. The mean volumetric water content at field capacity (pF = 2.5) and wilting point (pF = 4.2) are 28% and 14%, respectively. The soil bulk density is about 1.25 g cm^{-3}. For each soil sample, the volumetric soil water content at 11 pressure heads, h, was determined using a sandbox (for h = 0.01, 0.025, 0.1, 0.32, 0.63, 1.0 m) and a pressure plate apparatus (for h = 3, 10, 30, 60, 150 m). For each sample, the parameters of the van Genuchten (1980) model for the water retention curve using the Burdine (1953) condition were determined (Aiello et al., 2014).

Irrigation water has medium salinity ($EC_{25\,°C}$ equal to 2.02 dS m^{-1}), and pH equal to 7.30.

2.2. The partial root-zone drying experiment

Two irrigation treatments were used at the experimental field (0.4 ha) in a randomized block (about 600 m^2 each) design; each treatment had three replications, with three rows of 8 trees per row for a total of 24 plants per replica (Fig. 3). Perimeter trees were used as guards. The performed treatments were: a control treatment (T1) irrigated to replace 100% of crop evapotranspiration (ET_c), and a partial root-zone drying treatment (T4) irrigated