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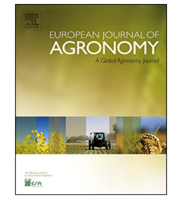

Are olive root systems optimal for deficit irrigation?

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ABSTRACT

In olive (*Olea europaea* L), deficit irrigation (DI) has proven to be an effective management strategy to improve water productivity (WP, yield per unit of water used), particularly under localized irrigation. However, despite the significant research efforts made to adapt irrigation programs to each particular cropping environment, little has been done to study the response of tree root systems to DI. The present paper analyzes the effect of water stress on olive root morphology and studies olive ideotypes best suited to DI. To do so, the results of a two-year field experiment using two irrigation treatments, a well-watered control irrigation (CI) and a regulated deficit irrigation (RDI), are combined with simulations using a soil-plant-atmosphere continuum (SPAC) model. Results of the field experiment show that olive root systems forage for water resources when RDI is imposed, i.e. they try to maximize the soil area explored. However, simulations indicate that under DI, foraging might not be the best strategy. Instead, a root system that tends to concentrate new growth inside the wet bulb will increase daily net assimilation (A_n) by up to 16%. The present analysis shows that tree performance under DI could be optimized to trigger a new leap in WP.

1. Introduction

Deficit irrigation (DI), has been successfully used as an agronomic practice to diminish the water used in irrigated crops, particularly trees and vines for which economic income is associated with fruit quality rather than biomass production. DI consists of reducing the water applied to below the maximum crop requirements to such a degree that the profits made from water savings overcome the loss of income from yield reductions, thereby increasing water productivity (WP, yield per unit of water used) (Fereres and Soriano, 2007). When this reduction is scheduled to match phenological stages with low sensitivities to water stress it is termed regulated deficit irrigation (RDI) (Chalmers et al., 1981). The precise induction of the stress relies on a good control of the water applied which can be achieved through systems with high uniformity of application like drip or micro sprinklers (Fereres and Soriano, 2007). During DI, some of the water transpired comes from irrigation and some from the soil reservoirs, which implies that the same DI program can induce substantially different levels of stress in the plant depending on the climate, soil characteristics and root architecture.

The role of the soil characteristics and the root architecture in the uptake capacity and the water relationships varies depending on the available water (Draye et al., 2010). When the soil is wet, root resistance is higher than soil resistance to water flow and water uptake tends to be proportional to the root length density (L_v) (Gardner, 1960). By contrast, under drought conditions, it is soil resistance that governs the flux of water to the plant (Draye et al., 2010). Consequently, in drought-prone environments, breeders have focused on the development of deep root systems with few long and thick laterals. Such systems maximize soil exploration and the chance to reach deeper wet layers (Wasson et al., 2012; Schmidt and Gaudin, 2017). On the other hand, for well-watered crops, a root system that tends to be confined to the wetted area with prolific laterals and root hair formation will perform better (Draye et al., 2010; Schmidt and Gaudin, 2017). However, a grey zone exists between the two extremes in which both soil and roots will drive the uptake flow (Draye et al., 2010). This blurred area compels to contextualize root traits to specific situations and to use tools like crops models to analyze ideotypes suited to the specific environments (Tardieu et al., 2017).

Olive (*Olea europaea* L) trees have traditionally been cultivated in the Mediterranean basin under rainfed conditions. However, in the last few decades, drip irrigation has been implemented in traditional and new olive plantations. As an example, in 2013 nearly 21% of Spain's harvested olive area was under irrigation, of which 98% used drip

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systems (MAGRAMA, 2013). Nevertheless, water restrictions in the main olive production regions have forced farmers to apply DI (Carr, 2013). Significant efforts have been made to study the best way to manage the stress during DI to maximize water savings while maintaining crop profitability. This is reflected in the large number of papers related to olive tree irrigation management (Carr, 2013). However, little attention has been paid to the crop itself. Olive trees have evolved to withstand the hot and dry summers typical of a Mediterranean climate. Such a capacity has been based on a set of avoidance and tolerance mechanisms (Connor, 2005). Under rainfed conditions, olive trees develop profuse root systems and are able to adjust root:leaf ratios to widely explore the soil, maximizing the capture of water resources (Dichio et al., 2002; Connor, 2005). In addition, low specific root length (SRL) values have been observed for pioneer and fibrous roots (Polverigiani et al., 2011). This trait is usually related to the ability to penetrate hard soil layers, and it is commonly encountered in trees developed in areas with contrasting wet and dry seasons, as occurs in Mediterranean locations (Huang and Eissenstat, 2000). However, it is not known whether the traits developed for rainfed conditions are optimal when applying DI.

Analyzing the effects of different traits on crop performance when DI is imposed is not straightforward given the number of non-linear relationships among the variables involved. To assist in such an analysis, a process-based model can be used to study the relationships between different traits of a crop and its performance (Martre et al., 2015). A soil-plant-atmosphere continuum (SPAC) model for olive trees has been developed by García-Tejera et al. (2017a) using a soil multi-compartment solution. Using this model, the heterogeneity present in the soil system when drip irrigation is applied can be captured and olive tree response under different degrees of water stress can be mimicked (García-Tejera et al., 2017a). The aims of the present paper are to study, in the field, the root morphology of an olive orchard submitted to two irrigation scenarios (well-watered and RDI) and to analyze the results using the SPAC model with a multi-compartment solution, providing insights into some key traits that might be useful in breeding programs aimed towards DI.

2. Materials and methods

2.1. Study area

The experiment was performed on a commercial hedgerow olive (*Olea europaea* 'Arbequina') orchard in Santa Cruz (Cordoba), Spain (37.7 °N, 4.6 °W, 170 m altitude) in 2013 and 2014. The soil was classified as a Vertisol with a clayey texture and a hard, calcareous layer at depths between 0.6 m and 1 m. Tree density was 1667 trees ha^{-1} (4 × 1.5 m). Each tree had a drip irrigation system comprised of three emitters with a discharge rate of 2.2 L h^{-1}. The plantation was established in 2005.

Two different irrigation treatments were imposed:

- Control irrigation (CI): Irrigation amounts were estimated as the difference between the evapotranspiration (ET) and rainfall, computing ET as the product of reference evapotranspiration (ET_0) and a crop coefficient (K_c). The K_c was set to 0.75, steady throughout the season, a value high enough to ensure a good tree water status.
- Regulated deficit irrigation (RDI): Each year, irrigation amounts for this treatment were exactly the same as those for CI except for a period running from June to August in which the water applied was gradually reduced each month to a specific percentage of that of the control (50% in June, 25% in July and 20% in August).

Each treatment consisted of one plot with 4 rows and 10 trees per row. Measurements were performed in the two central rows. Irrigation was scheduled to water the plants three times a week. Monthly irrigation volumes, evapotranspiration, and precipitation values are presented in Table 1.

Table 1
Monthly values of rain, evapotranspiration (ET_0) and irrigation in CI and RDI treatments.

Month	ET_0 (mm)	Rain (mm)	Irrigation (mm/day)	
			CI	RDI
2013				
January	29.8	78.5	0	0
February	40.1	90.3	0	0
March	57.7	241.9	0	0
April	104.1	58.9	0	0
May	136.6	36	0	0
June	170.2	2.2	48.79	29.73
July	198	2	160.54	55.94
August	176.8	59	127.86	43.89
September	123.1	12.4	94.40	84.54
October	78.6	32.2	59.35	43.29
November	46.1	13.8	0	0
December	29.9	142.4	0	0
2014				
January	24.5	114.3	0	0
February	33.3	109.9	0	0
March	70.6	11.4	0	0
April	104.2	24.8	35.27	34.11
May	150.1	11.5	64.52	64.83
June	160.4	3.4	70.36	57.51
July	176.0	1.4	147.43	36.24
August	164.2	0.0	144.72	24.69
September	105.6	37.2	84.79	71.5
October	67.8	93.3	24.77	29.25
November	33.2	194.4	0	0
December	18.2	32.4	0	0

Meteorological variables were recorded by a weather station located close to the orchard border. The station consisted of a sheltered air temperature and humidity probe (model HMP35, Vaisala, Helsinki, Finland), placed at a height of 1.7 m; a silicon cell pyranometer (model SKS 1110, Skye Instruments Ltd, Llandrindod Wells, Powys, UK), a propeller wind monitor (model 05103, RM Young, Traverse City, MI, USA) at a height of 2 m and a tipping bucket rain gauge manufactured in the IAS-CSIC laboratories (Cordoba, Spain) placed at a height of 0.4 m.

2.2. Root sampling design

Two different root sampling methods were carried out in 2013 and 2014 using an auger sampler with a 40 mm diameter. In August of 2013 (DOY 233), soil cores were extracted from CI and RDI in three representative trees of the same treatment from one of the two central rows of the experimental plot. Measurements were performed in a transect perpendicular to the dripper line at 0.25, 0.75 and 1.5 m from the emitter. Cores were extracted at soil depths of 0.15, 0.3 and 0.6 m. In September of the same year (DOY 253), a second sampling was performed on the same tree. Cores were extracted from a transect parallel to that of August 2013 (DOY 233) at a distance of 0.20 m. The same sampling protocol described for the August measurements was applied.

In August of 2014 (DOY 240), root length and biomass data were acquired from an intensive sampling of one tree of each treatment from one of the two central rows of the experimental plot. The selected trees were different from the ones used in 2013. Soil cores were taken from three transects parallel to the planting row at 0.25, 0.75 and 1.5 m from the drip line. In the transect at 0.25 m from the drip line, cores were extracted from the mid-point of segments of 0.25 m, while the sampling space in the other two transects was 0.5 m. As with the measurements in 2013, cores were obtained at three depths (0.15, 0.30 and 0.6 m). Fig. 1(a, b) represents the sampling design in 2013 and 2014.